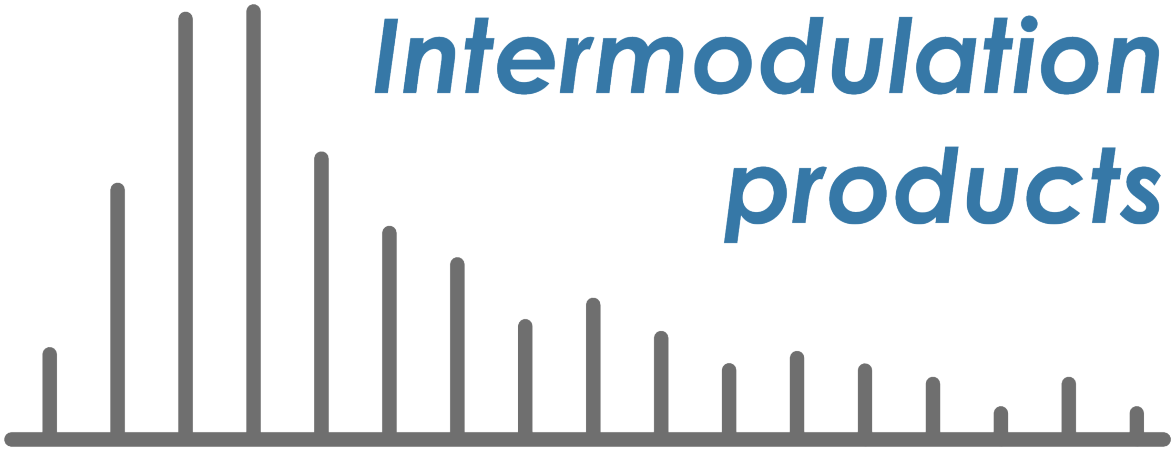


# IMP Software Suite User Manual

***Release 1.2***

**Intermodulation Products AB**

May 26, 2015

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CHAPTER

ONE

# INTRODUCTION

The **Intermodulation Products Software Suite** (IMP Suite) from Intermodulation Products AB is a collection of software tools for performing **Intermodulation Atomic Force Microscopy** (ImAFM™) – a powerful surface analysis method based on multifrequency AFM. This manual explains how to use the IMP Suite through its Graphical User Interface (GUI). The manual is used most effectively when the IMP Suite is open and running, taking data with your host AFM or analyzing already scanned data.

## 1.1 Conventions and useful tips

The IMP help icon appears at several places in the IMP Suite. Clicking on this icon will open a browser and jump to the appropriate place in the manual.

`Screen text` is denoted with a shaded box and it should coincide exactly with text in the IMP Suite; on a button, or next to a check box or input field.

The genindex contains key words and important screen text. Each entry is linked to the appropriate place in the manual. If you are wondering about the function of a button in the software use the help icon or search for the button name in the genindex.

Linked text (e.g. *The IMP Session and Work Flow*) cross-references to different parts of the manual. Use the back button on your browser or PDF viewer to return to the jump point.

Bullet lists are used to describe related items which appear in a group. For example, groups of radio buttons, control settings or groups of output fields, all related to a particular task.

## 1.2 Screen Layout

The screen layout in the software can be customized to suit the users needs, and the actual appearance depends on the computer platform used (Linux, Windows, Mac). A detailed discussion of how to customize the screen layout is given in the advanced section on *Panels and Views*. For this reason we do not make extensive use of pictures or screen shots in the manual, but rather `screen text` and icons .

## 1.3 Python

The IMP Software Suite is written in the computer language called Python, an open source language with many powerful tools for plotting, image analysis, and numerical calculation. These are collected in a set of modules called SciPy (Scientific Python)). The IMP Suite is platform-independent, running on Windows, Macintosh or Linux. Native graphics environments are used in the GUI which is written in wx-Python , so icons and panels may appear slightly different on different platforms.

This manual is written in restructured text language, and is available as HTML or PDF. The HTML version is linked with the help icons in the IMP Suite and it is more easily used when working with the Suite online. A separate software developer documentation describes the usage and function of the Python objects which make up

the IMP Suite. The developmer documentation is designed for users who want to enhance the functionality of the software by modifying the source code and programming their own measurement and analysis methods.

CHAPTER

TWO

# THE IMP SESSION AND WORK FLOW

## 2.1 Quick Start

Connect the intermodulation lockin to your host AFM and make sure the switch(s) on your signal access module are in the correct position. For details on connecting to your AFM, please consult the *Install Hardware* section.

Start the host AFM and set it to **Contact Mode**, with the **feedback set-point set to zero volts**. Here we assume that zero volts on the detector corresponds to the equilibrium position of the cantilever when it is free from the surface.

Start IMP Software Suite. A **session folder** named with the current date is automatically created where all your data will be stored.

## 2.2 The Work Flow

The work flow is symbolically represented by the left column of 6 Im icons. From top to bottom, these icons guide the work flow in the IMP Suite. Click on these icons to open the different panels and views.

**Find the resonance** by performing a *Frequency Sweep*.

**Calibrate the cantilever** using non-invasive thermal noise *Calibration*.

**Set up and start a scan** then engage the surface with the host AFM to start *Scanning*.

**Open previous scan files** and use the pixel and line inspectors to *Analyze Scan Data*.

**Add comments** to the automatic logging in the *Session Logbook*.

**View the session** and import host AFM data, batch process, or view 3D parameters maps in *Session Overview*.

Each step in the work flow is described in detail in the following sections:

### 2.2.1 Frequency Sweep

After loading the cantilever and adjusting the detector, we find the cantilever resonance by sweeping the frequency of the cantilever drive signal while measuring the detector response signal. The `Frequency Sweep` panel opens when you click the top icon in the work-flow.

`Run sweep` starts the measurement between the `Start frequency` and `Stop frequency`. Edit these fields to change the sweep range. The sweep range should include the likely resonance frequency of the cantilever, which should be provided by the probe manufacturer and is usually printed on the probe box. Reducing the measurement `Bandwidth` causes the sweep to be slower and the measured response to be more accurate. The sweep speed also depends on the `Number of points` recorded during the sweep.

Two check boxes provide automatic features for finding the resonance:

- `Locate peak` performs a second sweep with finer detail, zoomed in on the peak response found in the sweep range.
- `Transfer results to noise calibration` transfers the center frequency and estimated sweep range to the next stage in the work flow.

#### Correcting Driven Response

`Use Correction` is an advanced function that can be left unchecked for simple resonance-finding. This function is used to 'de-embedd' linear response from the measurement chain. Sometimes electronic equipment between the output or input of the Multifrequency Lockin Amplifier™ (MLA™), (see *Intermodulation Measurement*) and the host AFM can cause frequency-dependent amplitude and phase shifts to the signals that are measured by the MLA™. Use Correction compensates for any undesirable linear transfer of the signal due to these compenents 'embedded' in the measurement chain. The compensation is made using a procedure called de-embedding, performed in two steps:

1. A frequency sweep is performed while by-passing the AFM (insert a short in place of the AFM). After this sweep, press the `Set Correction` button, which transfers the result of this sweep to an internal correction file.
2. Put the AFM back in to the measurement chain and check the `Use Correction` check-box. All subsequent sweeps performed with this box checked will correct for the amplitude and phase shifts measured in the first step.

In summary:

- `Use Correction` will correct the measurement for an arbitrary *linear*, frequency-dependant transfer function embedded between the output and the input points of the measurement chain.
- `Set Correction` stores the last-measured transfer function to an internal file which is used for the correction.

### 2.2.2 Calibration

Quantitative AFM starts with a good calibration of the cantilever and ImAFM™ requires this calibration *before* you start to scan a surface. The IMP Software Suite contains the latest methods for cantilever calibration based on the measurement of the thermal Brownian motion of the cantilever and a theory of hydrodynamic damping of the oscillating beam. By fitting a theoretical model to the noise data we determine all constants necessary to the measure the cantilever deflection in meters, and convert this deflection to force in Newtons.

The calibration procedure applies to a particular cantilever eigenmode (resonance). Details and references to the literature are given in the advanced section on *Noise Calibration*. Here we describe how to perform the calibration. The tab at the very top selects between calibration of a `Flexural` or `Torsional` eigenmode. The procedure is very much the same for either type of mode, but the underlying formulas and analysis are different. We begin by describing calibration of flexural eigenmodes, and end with a discussion of torsional eigenmodes.

#### Choose Cantilever and Method

`Calibration Parameters` specifies the type of cantilever and calibration method.

- `Temp [C]` is the temperature of the damping medium in Celsius, used to determine the magnitude of the thermal noise fluctuation force driving the cantilever.
- `Fluid` selects the density and viscosity of the medium surrounding the beam, needed for calculation of hydrodynamic damping. Noise calibration methods have not been tested thoroughly beyond studies in `Air`, but we include to option to apply the theory in `Water 20 C`.
- `Cantilever` selects from a list of pre-programed cantilevers for which calibration constants have been published. If your cantilever is not on this list you can choose `Arbitrary Rectangular` and enter the `Length` and `Width` , or plan-view dimensions of your rectangular beam cantilever. You can edit the length and width fields for any chosen cantilever without changing the stored values for pre-programed cantilevers. Alternatively, you can *Add Edit Remove cantilevers* as described below.
- `Method` selects between six methods of calibration:
  - `Hydrodynamic function` uses an analytic expression for the hydrodynamic function to calculate the damping. The calculation applies to a rectangular beam in the limit length >> width (see *[Sader-1998]*). This method uses length and width given in the fields above.
  - `Sader constants` uses a good approximation to the hydrodynamic function described with three parameters $a_0, a_1, a_2$ that are specific to a particular cantilever. These constants have been measured and checked against other methods and according to theory they should apply to any cantilever of the same shape (see *[Sader-2012]*). For this method, the length and width fields have no influence.
  - `Reference calibration` brings up three fields. If you have one good calibration using another means, such that you know all three constants: the quality factor, stiffness and resonant frequency, or `Q-ref`, `k-ref` and `f0-ref` respectively, you can use this calibration as a reference for calibrating other cantilevers of the same shape (see *[Sader-2012]*). For this method, the length and width fields have no influence.

- `Thermal tune: responsivity` brings up a field to enter the known stiffness of the cantilever fundamental eigen mode, `k [N/m]`. The thermal noise measurement is then applied to determine the detectors inverse responsivity [nm/V].
- `Thermal tune: stiffness` brings up a field to enter the known detector inverse responsivity, `Inv. resp. [nm/V]`. The therm noise measurement is then applied to determine the cantilever mode stiffness.
- `Manual` overrides the thermal noise measurement and no hydrodynamic damping theory is applied. All four calibration constants are entered in the fields given: the eigenmodes resonance frequency `f0 [Hz]`, dimensionless quality factor `Q [-]`, mode stiffness `k [N/m]`, and the detectors inverse responsivity `Inv. resp.[nm/V]`.

### Measure noise

`Acquire Data` controls the start of measurement, saves data, or loads previous measurement data.

- `Run calibration` starts the averaging of many separate noise measurements, to decrease the fluctuations in the noise data. If *Frequency Sweep* was used to find the resonance and `Transfer results to noise calibration` was activated, the software will automatically analyze an appropriate frequency range around the resonance. The *Status Banner* indicates the progress of the calibration.
- `Settings` opens an `Acquisition Settings` dialog box where you can select the total number of `Measurements` in the average, the `Center frequency [kHz]` and `Frequency span [kHz]` to analyze, and the `Frequency resolution [Hz]` between data points. You can also give a `Down-sampling` factor which averages the given number of samples before transferring to the computer for spectral analysis.
- `Save As` opens a dialog box to save the noise data to a .txt file. If `Autosave` is checked, this file will be automatically saved. The file is saved in the JSON format, and it can easily be opened in many different programing languages (Matlab, Python, Java, etc.) It is not necessary to save the raw noise data for each calibration, as the software automatically keeps track of the *Current calibration*, or most recent fit of calibration data, which is stored as the relevant calibration in the scan file.
- `Load` opens a dialog box to load a previously saved noise data.

### Fitting noise data

When the `Enable Fit` box is checked, the fit is performed in real time and displayed in the plot as a solid blue line. The noise contribution from the cantilever motion is shown with the yellow dash line. For a full description of the theory and fit, see *Noise Calibration*.

Sometimes very low level spurious signals can be picked up when measuring noise. If the spurious signal is not driving the cantilever, you can remove improve the calibration by removing them from the fit. Select the following tools in the calibration plot toolbar:

- right-click-and-drag on the plot will select a range where the fit will be performed. Data outside this range becomes grey and is not analyzed in the fit.
- clears the selected fit range.
- right-click-and-drag defines an area over which data points are ignored in the fit. The removed data is marked with a red x.
- clears all ignored data.

### Calibration Result

The `Calibration Result` is displayed in several ways giving you important figures of merit. It is useful to think of the calibration as having two parts: The calibration of the cantilever (the force transducer) and the

calibration of the detector (the deflection sensor, or optical lever).

`Cantilever:`

- `Resonance frequency` $f_0 = \sqrt{k/m}$[kHz] of the simple harmonic oscillator model used to model the cantilever eigenmode with mode stiffness $k$ and effective mass $m$.
- `Width of resonance` $\gamma$[Hz] related to the damping coefficient of the simple harmonic oscillator model. $1/\gamma$ is the characteristic time for exponential decay of oscillation amplitude due to the damping of the surrounding medium.
- `Quality factor` $Q = 2\pi f_0/\gamma$ is the ratio of the energy stored in the oscillation, to the energy lost per cycle of oscillation. A freely oscillating cantilever will 'ring' for $Q$ cycles before the amplitude decays by a factor of $1/e$, or 37%.
- `Cantilever stiffness` $k$[N/m] is the eigenmode stiffness, or the coefficient of the linear restoring force in the simple harmonic oscillator model.
- `Thermal noise force` $[\text{fN}/\sqrt{\text{Hz}}]$ is the fluctuation force associated with the linear, viscous damping of the cantilever. This frequency-independent force noise gives rise to a peak in the deflection noise near a high-Q resonance. The thermal noise force represents a fundamental sensitivity limit for force measurement (see *Note on sensitivity and accuracy*).

`Detector:`

- `Inverse responsivity` $|\alpha|^{-1}[\mu m/\text{V}]$ is the inverse magnitude of the detectors response function, which converts the measured signal in Volts [V] to a deflection of the tip in meters [m]. In the literature, this constant is often referred to as the 'inverse optical lever sensitivity' (invOLS), but we prefer the term ' responsivity' (see *Note on sensitivity and accuracy* for further discussion) . The calibration performed here actually does not rely on a calibrated measurement of voltage by the MLA™, nor does it rely on the calibration of the AFM scanner to determine detector responsivity. The software uses the noise measurement to determine cantilever deflection in the digital counting units of the MLA™, or Ananog-to-Digital units [ADU]. Thus, the noise measurement and hydrodynamic theory together become a *primary* form of calibration that does not depend on the calibration of any other equipment, apart from the thermometer measuring temperature.
- `Noise floor` $[\text{fm}/\sqrt{\text{Hz}}]$ is the detector noise, expressed as an equivalent deflection noise of the cantilever. This figure is the correct measure of the sensitivity of the opto-electronic system which detects the cantilever deflection.
- `Equivalent force` $[\text{fN}/\sqrt{\text{Hz}}]$ expresses the detector noise as and equivalent force noise acting on the cantilever. This equivalent force noise gives the sensitivity of force measurement, if the same cantilever were to measure force quasi-statically, or at low frequency well below resonance.
- `Peak to flat ratio` [dB] is the ratio of the noise peak (thermal noise) to the flat background noise (detector noise). If you compare two measurements with the same cantilever, the larger this number, the better your detection (see *Note on sensitivity and accuracy*).

### Current calibration

Running a new calibration, loading a previous calibration, selecting a new range or excluding points, runs the fitting routine which determines all the calibration constants. These constants define the **current calibration**. After each scan, all calibration constants from the current calibration are stored with the scan file, together with the raw spectral data acquired by the MLA™. It is not necessary to store a calibration file in order to analyze the data in scan file. The `Store` and `Load` features are there only if you want to store or view raw noise data for a particular run of the calibration. The raw noise data will be saved for each run if `Autosave` is checked. It is very easy to re-calibrate during a scan session and thereby re-define the current calibration. Simply stop the scan, retract the probe from the surface, and re-run the calibration. We recommend that you re-calibrate frequently, to check if anything has changed with the cantilever and detector. Calibration should also be re-run if any adjustments have been made to the laser or the detector, and it must be performed with every new cantilever, before you start to perform ImAFM™.

#### Add Edit Remove cantilevers

`Add / Edit / Remove` opens a dialog box that allows you to change calibration parameters of one of the stored cantilevers, or to create a new cantilever.

The `Add` tab has two options:

- `Basic` is for rectangular cantilevers. Enter the `Length, L [um]` and `Width, b [um]` in micrometers, and the cantilever name and manufacturer. Click `Add` and your cantilever will appear in the pull-down list. The calibration method will will be based on the theoretical expression for the hydrodynamic damping function, valid for $L >> b$ (see `Method` above).
- `Advanced` is for cantilevers of arbitrary plan-view dimensions. Here you can enter the `Sader Constants` if they are known, or the calibration parameters of a `Reference calibration` for a cantilever of the same plan view dimensions (see `Method` above). Length and Width are interpreted as effective values for a non-rectangular cantilever.

The `Edit` tab allows you to change calibration parameters of the selected cantilever.

The `Remove` tab allows you to remove a user-added cantilever from the selection list.

#### Calibrating torsional eigenmodes

Torsional calibration uses the same principal flexural calibration. It is currently under development and two methods are available:

- `Hydrodynamic Function` uses the analytical expression for the hydrodynamic function of a long rectangular beam, calculated by Green and Sader [Green-????]. This method calibrates the fundamental eigenmode and it uses length and width given in the fields above.
- `Thermal tune: stiffness` brings up a field to enter the the height of the tip, or the distance that the tip is offset from the principle axis of the cantilever beam ???.

### 2.2.3 Scanning

Before you begin, the host AFM must be configured for ImAFM™. If no special ImAFM™ mode is provided on your host AFM, simply put it in **contact mode** with the feedback **set-point set to zero volts**. The MLA™ generates a 'fake' deflection signal and the host AFM will preform scanning feedback on this signal (see *Connection to host AFM*). The feedback parameters, integral and proportional gain, are set in the host AFM software.

The default scanner view has three components: The `Scanner` panel, the `Image Settings` panel and the main view showing the `Amplitude` and `Phase` images. More panels can be added, for example when you want to perform analysis as you scan, making force curves or analyzing transects. These panels will be addressed in the section on *Quantitative Analysis*. Here we describe how to setup and execute the first scan.

#### Setup and Scan

Three controls in the `Scanner` panel specify the parameters for `Setup`. There must be a *Current calibration* in order for the setup to function.

- `Osc. range` is the desired maximum amplitude of oscillation (peak-to-peak) in nanometers of the cantilever when it is free from the surface. When the surface is engaged, the oscillation range will be somewhat reduced, depending on the `Amplitude set point`.

- `Mod. range` is the range over which you want to modulate the amplitude. The amplitude will be modulated from the minimum value ( `Osc. range - Mod. range` ) to a maximum value `Osc. range`. The tip-surface forces will be measured over this range. Typically you want to measure from zero deflection, up to the peak value of the cantilever deflection. In this case you set the modulation range to one half of the oscillation range.
- `Pixel rate (df)` is the spacing $\Delta f$ between tones in the frequency comb (see *Intermodulation Measurement*). The pixel rate, together with the number of pixels per line determine the `scan rate`.
- `Resolution: x y` sets the number of pixels to acquire in the fast scan direction (x) and the slow scan direction (y). The **x resolution** does not depend on the host AFM setting of pixels per scan line. The x resolution together with the pixel rate determines the `Scan Rate` given by the IMP Suite. The scan rate must be set on the host AFM to the value given by the IMP Suite. The **y resolution** must also be set to the same value on the host AFM, which determines the number of scan lines at the given rate.
- `Setup` runs a routine to determine the frequency and amplitude of the two drive tones. If you get an *Out of Range Error* message you may need to adjust the oscillation range or attenuate the input signal (see *Advanced Setup*). This automatic setup is designed for basic ImAFM™ with two drive tones close to resonance. Much more complicated measurements and modulation schemes can be setup with the *Drive Constructor*. When the setup is complete, the `Scan` button will not have gray text, indicating that you are ready to scan.

`Scan` makes the software ready to acquire measurement data. After pressing `Scan`:

- Set the scan rate on the host AFM to the `Scan rate` given in the scanner panel.
- Make sure your host AFM is set to **contact mode** and the set-point is set to **zero volts**.
- Engage the sample and start the scan in the host AFM software.

When the end-of-line (EOL) triggers are detected, the IMP Suite will begin to collect and display the scan data. After the last scan line when an end-of-frame (EOF) trigger is detected, a scan file is stored (see *Status Banner*). However, the EOL and EOF triggers do not code for the direction of the scan. It may be necessary to sometimes `Flip left-right` or `Flip up-down` to make your image match that displayed on the host AFM.

On some AFM's you can move to the top or bottom of a frame to start a fresh scan without waiting for the current scan to finish. If this action is performed on the host AFM, and if the EOF trigger is sent, the IMP will save a scan file and automatically start collecting a new scan. Some AFM's (notably Asylum) do not send and EOF trigger when you move to the top or bottom of a frame. When the IMP suite is configured for such an AFM, two buttons appear which allow you to `Move to top` or `Move to bottom` to keep the synchronization with the host AFM scan.

During the scan, you can at any time perform the following actions and set the following parameters:

### Measure free, set-point, scan rate

`Measure free` causes the cantilever to be pulled away from the surface where a new measurement of the free response is made. The tip-surface force is determined by subtracting the free response from the engaged response. The free response is automatically measured durring `Setup`, but not between continuously acquired scans. The most recent measurement of the free response is stored with the scan file when it is saved at the end of the scan, and this most recent measurement is used for subsequent analysis. Often the cantilever needs to 'settle in' after engaging a surface, and a new measurement of the free response is required after some time of scanning. We recomend that you press `Measure free` if your force curves appear strange, to check and see if this makes a difference.

`Amplitude set-point` is the set-point for the AFM feedback. Feedback is based on the response amplitude at one of the two drive frequencies (Drive 1), and the set-point is given as a percent of the free response amplitude at this drive frequency (see *Setup Feedback*). To engage the surface, this set-point must be below 100%. Setting the set-point to more than 100% will cause the probe to lift from the surface – a useful way to lift away from the surface without stopping the scan, if you want to check or adjust something.

`Scan rate` is the required rate of scanning as determined from the pixel rate and x resolution. The scan rate is determined by the chosen pixel rate (measurement bandwidth, df) and number of pixels in the scan line (x resolu-

tion). You must set the host AFM to scan at the given scan rate, otherwise the images will not be synchronized. Some host AFMs do not allow arbitrary scan rate and it is not necessary that the scan rates match exactly. A 1% deviation is not noticeable in the images, but one should set the host AFM scan rate slightly smaller than the ImAFM™ scan rate. You can slow down the scan rate using the same measurement bandwidth and pixel rate, to help track better on a rough surface. `normal` means scanning at the maximum rate and you can choose `half` or `quarter` speed. Making this choice will result in a new calculation of the scan rate which must be set in the host AFM. Slowing down the scan will help to track the surface more closely, making the force measurement more accurate.

You can also change to new values of `Osc. range` and `Mod. Range` during a scan. Input the new values ad press `Setup`. The cantilever will lift and perform a new setup routine, adjusting to the new parameters. However, you can not change the value of `Pixel rate (df)` without first stopping the scan and lifting away from the surface.

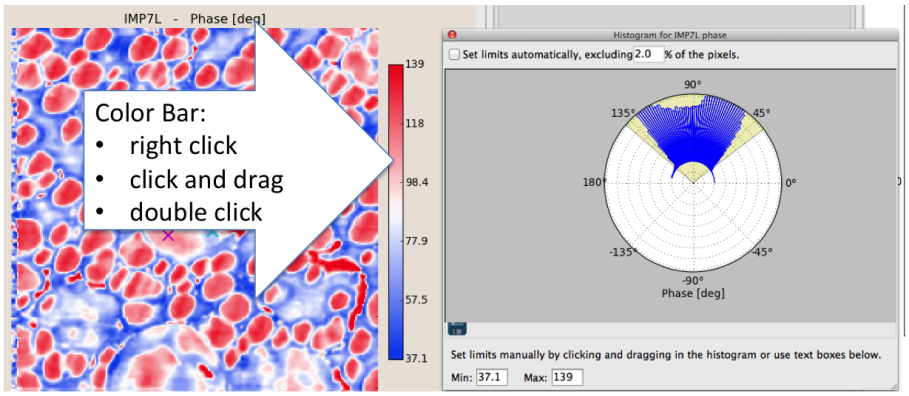
### Image settings

The panel `Image Settings` contains the controls for displaying which images are plotted

- `IMP Control` lets you select the frequency at which the `Amplitude` and `Phase` images are plotted. The frequencies are ordered from lowest to highest, going from left to right. The text below the slider displays which frequency is being plotted
- `Scan direction` has two buttons which control whether the `Trace` or `Retrace` will be plotted. Data is acquired and stored for both scan directions. Note that both trace and retrace are always stored in every scan. Flipping between trace and retrace can be a good way to see if feedback errors are affecting your image.
- `Swap` will exchange the data stored as trace and retrace. The host AFM trigger signals do not distinguish between different scan directions, and sometimes it is necessary to swap so that trace and retrace are the same as that in the host AFM. Do not worry if you do not get this correct during the scan as it can be easily corrected after the scan session using the *Session Overview*.
- `Flip right-left` and `Flip up-down` do not exchange trace and retrace data. This action can also be done later in the *Session Overview*.
- `Scan size` , when checked, will display axis labels with the image size which must be entered in the `x` and `y` data fields. Units should be given in either nanometers or micrometers, using the characters: nm, um or µm (u will be displayed as µ). Scan size values will be stored when the scan is saved, and these values will be overwritten if and when the scan size is imported together with height data from the host AFM (see *Import host AFM data*).

#### Color Bar

The color bars have functionality for adjusting the images:




- **Right click** on the color bar to see a histogram of the plotted values. You can adjust the image contrast by left-click-and-drag on the borders to the shaded region. These borders mark the max. and min. values for

the color map used. Data outside the shaded region is forced to either min. or max. If the check box is activated, the software will automatically choose the max. and min. excluding the given percent of outlying values. You can also change the color map in the histogram window.

- **Click-and-drag** upward or downward on the color bar, to adjust the minimum and maximum values respectively. The color value of the center will remain constant. You can do this action with the histogram open.
- **Double click** on the color bar to return to the automatic setting settings.

#### Image Toolbar

All plots and images have a toolbar with the following functions:

**Home, Forward and Back tools**

The home tool to returns to the initial plot or the full image. The forward and back buttons move through the successive plot views which the software remembers after each zoom or pan action.

**Pan-Zoom**

When selected, left-click-and-drag will cause the plot to zoom, starting from the point of click. Dragging horizontally will zoom only the x-axis, dragging vertically will zoom only the y-axis. Dragging at an angle controls the relative rate of zoom of each axis. Right-click-and-drag will grab the plot at the point of click and slide it in the direction of the drag. Performing these actions while holding down the **x**, **y** or **ctrl** keys will restrict the pan or zoom to occur only in the x-axis, y-axis, or preserving current aspect ratio, respectively.

**Zoom**

When selected, a right-click-and-drag over the plot will zoom to the selected rectangle upon release.

**Save image**

Opens a dialog box for saving the image in several formats (png, eps, pdf and more). Sometimes you would like to change the aspect ratio of the plot, or the relative size of the frame and text in your saved image. Simply rescale the entire suite (click-and-drag on the lower right corner), or re-size a particular frame, before you save. This action will rescale the plot and axes while keeping the text and line size fixed.

**Configure subplots**

The subplots icon opens up a dialog box to adjust the placement of the plot axes within the plot frame.

### Selecting Data in a Scan

Two important tools in the image toolbar are the pixel inspector and line inspector tools. These tools do more than simply controlling the plot. They select data at pixels and analyze the data to generate force and parameter plots.

**Pixel inspector tool**

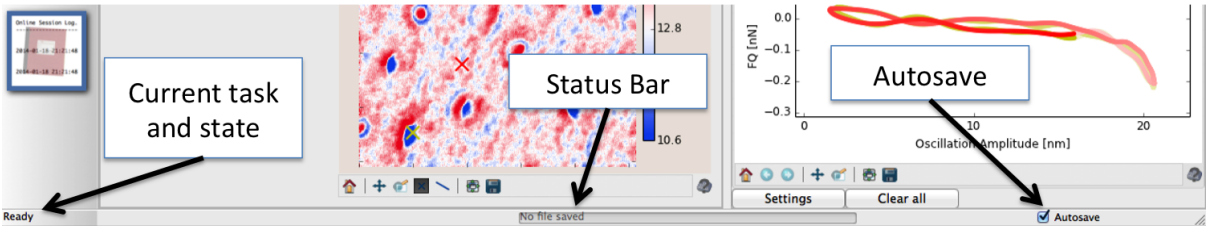
A left-click on the icon will activate this tool. When the tool is activated, a right click on either the amplitude or phase image will select the data at the point-of-click, mark it with an **X**, and open the *Signal Inspector* panel. If you have the *Quantitative Analysis* tools installed in your software, the *Force Inspector* will also open and display a force curve. When the pixel inspector tool is active, left-click on the plot will un-select the **X** nearest to the point-of-click and remove the data from the *Data Tree*. The *Quantitative Analysis* tools allow you to analyze the spectral data in many different ways to reveal tip-surface interaction. The *Data Tree* allows you to compare different pixels form the same scan, or different scans, in the same plot.

#### Line inspector tool

A left-click on the icon will activate the tool. When active, a right-click-and-drag on either the amplitude or phase image will select a transect line upon release and a left click will un-select the line nearest to the point-of-click. The `Line Inspector` panel will open and a plot of the amplitude and phase of the currently viewed image will be shown. All data along this line will be selected and available for analysis. If you have the *Quantitative Analysis* tools installed in your software, the line inspector will allow *Analyzing Linear Transects* and plot parameters of the tip-surface interaction along the selected transect.

### Status Banner

The banner at the very bottom of every view has text describing what task the software is currently performing (sweeping, calibrating, scanning, etc.) and a status bar that graphically shows the time required to finish the task. If `Autosave` is checked data is continuously saved to file save when the task is finished. The name of the most recent saved file is also given.




## 2.2.4 Analyze Scan Data

One aspect of ImAFM™ which makes it so powerful is that all raw data, trace and retrace, are stored in one compact scan file. The intermodulation spectrum at each pixel is an optimally compressed representation of the cantilever motion, from which we reconstruct the tip-surface force. With the raw data stored in the scan file, the AFM scientist can go back and make a more careful study of each point on the surface, analyzing it with different models and plotting it in different ways. To fully appreciate the analytical power of Intermodulation AFM, you should have the *Quantitative Analysis* package from Intermodulation Prodcuts.

In `File` pull-down menu, select `Open (ctrl+O)`. The `Amplitude` and `Phase` images appear in a new tab for each open scan file. You can open multiple tabs and compare data from different scans on the same plot in the analysis view. In the analysis view you will find the *Image settings* panel, the *Image Toolbar* and the *Color Bar* which have functions previously described. With the *Pixel inspector tool* and *Line inspector tool*, you can select individual pixels and lines for *Quantitative Analysis*.

### Image Smoothing

The analysis panel has an additional `Smooth image` button, which opens a smoothing dialog box where you can apply a Gaussian filter to your scan data. This filter will convolve the stored intermodulation data with a Gaussian function of width in x and y given by `Sigma`, in pixels. The result is a new image, stored to the given `File name`, where each pixel of the new image is a weighted average of neighboring pixels in the raw scan data file. Smoothing with one pixel results little loss of sharpness in the image but it lowers then noise considerably. The Gaussian has 98% of the weight within 3 Sigma of the center, so smoothing with one pixel essentially averages a block of 9 pixels, giving an improvement in the signal-to-noise ration by a factor of 3. This is a smart way to improve the signal quality without increasing the measurement time, based on the assumption that neighboring pixels are more likely to have the same response. Note however that smoothing does introduce a correlation length

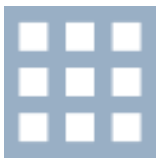
to your data, which you can clearly see as a grainularity in high-order IMP images, which are often more noisy. Be careful not to interpret these smoothing-induced grains as features in your image.

### 2.2.5 Session Logbook

The Intermodulation AFM Software Suite keeps a session log while you are working. This log file is a text file formatted for easy reading so you can quickly see exactly what was measured and when it was measured. The software automatically logs all important activity in chronological order with a time stamp. For example: making a new calibration, storing an image, starting or stopping the scan, and much more.

You can also add your own text comments to the log file. Add your comment to text field at the bottom of the panel and finish with `Ctrl+Return`. Your comment will be time stamped in inserted in to the log file.

### 2.2.6 Session Overview



This view shows all the scans in a session, automatically imports data from the host AFM, sorts out unwanted scans to a sub-folder, adjust images for synchronization problems with the host AFM, and generates parameter maps on multiple scans in a batch processing mode.

#### Session

`Open IMP session` and choose a session folder. An overview is generated showing file info and image thumbnails where each row corresponds to one scan. `Reload` causes the overview to be updated to the current state of the session folder. `View session log` opens a window showing the session log file.

#### Import host AFM data

The AFM height image is a record of the change of the probe height during the x-y scan. The probe height $h$, is the position of the base or the fixed end, not the position of the tip $z$ at the free end, of the flexing cantilever (see drawing in the section *Force Reconstruction Methods*). The probe height is controlled by the feedback while scanning, and in most modern AFMs the height signal is measured using a linear sensor built in to the scanner. When performing ImAFM™, the height data is recorded by the host AFM. To associate ImAFM™ quantitative analysis with surface topography, it is necessary to import the height data in to the IMP Software suite.

`Associate host AFM files`

- `Import height data` : Navigate to the folder on your host AFM computer, network or storage device where the host AFM files are stored. When you OK the selected folder the `Match Images` window opens. Drag the image thumbnails from `Unmatched IMP images` at the bottom, and drop them on the corresponding `AFM images` at the top. When you have matched a few images, click `Match with timestamps` and the computer will attempt to associate all remaining files. If the matching is incorrect, you can drag images away from middle group of `Matched IMP images`. When the matching looks correct, click `OK` and a copy of the AFM height data files will be stored in the ImAFM™ session folder with the scan number (i.e. **scan01234_**) prefixing the host AFM file name. The AFM height data will remain in the same file format as the Host AFM. (Note: In DI/Veeco Nanoscope software version 5 there is a bug

which requires you to simply open and close the file in the DI software before you can import it to the IMP suite.)

- `Hide unchecked` will move all the unchecked scans to a sub-folder of the session folder called 'hidden_scans'. These scans will no longer be displayed in the session overview, but they are not erased. You can always use your computers file browser to move a file from the 'hidden_scans' folder back to the session folder, where it will again be displayed when you click `Reload`. `Unhide all` brings all files from the 'hidden_scans' sub-folder up to the session folder.

### Flip and swap scans

Because the host AFM does not code the trigger signals for trace and retrace (only for change of fast-scan direction) it may be necessary to left/right flip the scan data or exchange the trace and re-trace data in order to associate the ImAFM™ scan correctly with the host AFM scan. Furthermore, AFM triggers do not code for slow scan direction (only end of frame) so it may be required to exchange up/down flip images. All this is easily done in the Session Overview. To perform these these flip and swap operations you first have to select the scans.

`Checkmarks` control which files will be flipped and swapped: `Check` will select all scans, `Uncheck` deselects all scans, `Toggle` will switch checked to unchecked, and unchecked to checked.

`Apply to checked scans`

- `Flip Left/Right` is performed on both trace and retrace data, but trace and re-trace are not exchanged.
- `Flip Up/Down` is performed on both trace and retrace data, but trace and re-trace are not exchanged.
- `Swap Trace/Retrace` will exchange trace and retrace, with out performing any flip. Note that left-right flip, does not necessarily imply that trace and retrace were stored incorrectly when scanning. Depending on whether you selected the trace or retrace for storing the height data in the host AFM, you may want to exchange trace an retrace to get correct association. ImAFM™ always stores both trace and retrace.

### Batch process parameter maps and force volume data

`Analyze checked scans` in the *Session Overview* lets you set up and run a batch process to make parameter maps on several files.

- `Paramter Map: Model fit`, when checked, will perform the analysis described in *Model Fit*, generating parameter maps, or color coded images of tip-surface force parameters. The `settings` button opens a panel for choosing the model and fit parameters, as described in *Parameter Maps*.
- `Paramter Map: Polynomial`, when checked, will perform the anaysis described in *Fast Polynomial*, based on the polynomial representation of the conservative force-distance curve. The `settings` button opens a dialog with options similar to that for *Parameter Maps*. `Polynomail degree` is desribed in *Polynomial*.
- `ADFS Force Volume` , when checked, will perform *Amplitude Dependent Force Spectroscopy (ADFS)* on each pixel of an image. The `settings` button opens a dialog with options similar to that for *Parameter Maps*. `Save to HDF5` will create one file containing an ADFS force curve at each pixel, whereas `Save to ASCII` will create a folder with one file for each pixel, where the pixel coordinates are given in the file name.
- `Start` the batch processing for all checked scans. A status bar tells you how far the batch process has progressed. `Abort` will end the process, storing the data analyzed thus far. It is not possible to resume an aborted process.

### Three dimensional viewer

To generate a three dimensional view you must have imported the height data from your host AFM. **Double click on the height image** to open the `IMP 3D-viewer`.

If you have generated a parameter map for the scan in question, the 3D viewer will paint a color map of a parameter on to a 3D projection of the height data. In the `Viewer settings` group, the check box `Same color-bar`

will force the 3D viewer to use the same limits for all parameter images of the same type. This feature makes it much easier to compare parameter maps between different scans.

When the viewer is open, you will see functionality for:

`Save image as...` where you can save to a desired location, and choose between several different file formats.

`Image settings`

- Choose the `Size` of the image in pixels. Resizing the viewer to changes these numbers and their aspect ratio.
- `Background color` can be chosen to something other than the default gray.
- `Text color` will effect the X and Y size labels.

`Sample settings`

- `Z scale` sets the aspect ratio of the Z scale, in relation to the X and Y scales. This aspect ratio is displayed below the image, together with the Peak height in nanometers, or the height of the tallest feature in the image.
- `Parameter` is pull down menu listing all parameters of the model which was fit to the scan data. Here you select the parameter which you want to display as a color map, on the 3D view of the height data. Note that parameters which where were unchecked in the fit settings, were not adjusted and will therefore show only one color corresponding to their fixed value.
- `Limits` opens up a window with a histogram of the parameter values. The shaded region is that covered by the color bar. Everything outside this region is displayed as white. You can click and drag on the left and right edges of this region to adjust the color bar limits, or input the `Min:` and `Max:` values manually. The check box at the top allows you to activate an automatic routine to adjust the limits, excluding the given percent of pixels in the upper and lower tails of the histogram.

`Camera position`

- `Azimuth` and `Polar` angles can be entered as degrees, or left click and drag on the 3D image.
- `Distance` is changed by adjusting the control, or right click and vertical drag on the 3D image.

`Plane fit` has three different methods for flattening the image:

- `None` shows the height data as it is stored in the host AFM height image file.
- `Average` fits a plane over the entire image and offsets all height data so that this plane is flat.
- `Selected points` allows you to flatten on a selected region of the image. With this option selected, hover over the image with the mouse. When you press the 'p' key, the point at the mouse arrow will be selected. After selecting 3 points a plane can be calculated and the image will offset all height data so that this plane is flat. You can continue to select more than 3 points, and the image will be flattened with a best-fit plane to all selected points. The `clear` button removes all selected points. A red frame appears when you select points. To make this frame disappear, hover outside the image and press the 'p' key.

CHAPTER

THREE

# QUANTITATIVE ANALYSIS

The quantitative analysis tools allow you to analyze the measured intermodulation spectral data at each pixel in a variety of ways. Each spectrum is a frequency-domain representation of the tip motion at that pixel, and from this motion we determine the tip-surface force. We may refer to this analysis as **inversion** because it involves solving an inverse problem, or that of finding the force which produced the measured motion, as opposed to forward problem of finding the motion resulting from a given force. As is often the case, the inverse problem is 'ill-posed'. The limited sensitivity of our measurement gives inadequate information for finding a unique solution to the inverse problem. The very small force that we are trying to determine only gives measurable motion at frequencies in a narrow band close to the high-Q cantilever resonance. Our challenge is therefore to reconstruct the force from this partial spectrum, or narrow band response. Fortunately, with enough intermodulation spectral data, and with a few assumptions that are not so very restrictive, we can find useful solutions. We call the solution of this inverse problem **force reconstruction** , or reconstructing the force from the intermodulation spectrum.

In dynamic AFM there are several forces giving rise to the cantilever motion: The tip-surface force, cantilever bending forces, viscous drag force on the cantilever body, and the inertial forces due to acceleration of the cantilever mass, including the drive force resulting from the shaking of the cantilever base. To properly separate out the tip-surface force from all other contributions we require two things: A good calibration of the cantilever (see *Calibration*), and a good measurement of the cantilevers free motion when it is far away from the surface (see *Measure free, set-point, scan rate*).

Calibration is performed at the outset of ImAFM™ and the free motion is measured before scanning. It is easy to re-do either of these at any time during the session. We recommend that you check the calibration and perform a new measurement of free oscillation occasionally, to see if the results are consistent with previous measurements. The most recent calibration data and free motion spectrum are stored with each scan, at the end of the scan. These measurements are an important part of the analysis of the scan data.

The focuses in this chapter is on how to use the software to perform different methods of analysis. References are given to the scientific literature where the fundamental physics and mathematics of the force reconstruction methods explained are explained in detail.

## 3.1 Inspecting single pixels

The intermodulation spectra at individual pixels can be analyzed by selecting the data with the *Pixel inspector tool*. This puts the data in to a *Data Tree* and it allows you to examine it in the following panels:

### 3.1.1 Signal Inspector

Activate the *Pixel inspector tool* in the *Image Toolbar*, and left-click on a point in either the `Amplitude` or `Phase` image to select a pixel (right-click to de-select). The data from this pixel is moved to the *Data Tree* and the `Signal Inspector` panel opens where you can see the tip motion durring the selected pixel time. You can display the motion in the following ways:

- `Time` signal shows a very dense plot of fast oscillations with a slowly varying amplitude envelope. Zoom is required to see the individual oscillation cycles.

- `Spectrum` shows only the amplitude of the individual intermodulation frequency components, ploted on a log scale. The component which is plotted with a thicker line corresponds to the amplitude and phase image displayed. You can click on different componets in the plot, and the amplitude and the images will change to the amplitude and phase of that frequency component.
- `Phasor` shows a plot where both amplitude and phase are plotted in a polar plot, or as vectors in a complex plane.

### 3.1.2 Force Inspector

If the *Quantitative Analysis* software is installed, selecting a pixel with the *Pixel inspector tool* will open the `Force Inspector` panel where you see plots of the analyzed spectral data, giving information about the interaction forces at each pixel. Note that the physical units in the plots are given in calibrated nano-Newtons [nN] and atto Joules [aJ = nN nm] vs. nanometers [nm], as determined in the *Calibration* step.

The Force Inspector panel has three tabs `FI FQ Work Force` which select the different plots as described in detail below. The `Settings` button opens a panel where you find three corresponding tabs to control the different plots.

- `Force Inspector Settings` panel, `FI FQ` and `Work` tabs:
  - `display options` are chosen through a pull-down menu that allows you to select different regions of the curve for plotting. Typically you want to choose `multi-valued curves` which shows $F_I(A)$ and $F_Q(A)$ for both increasing and decreasing oscillation amplitude in the beat-cycle of one pixel.
  - `Use shading` check box will activate a shading of the $F_I(A)$ and $F_Q(A)$ curves, such that the lightest shade corresponds to the start of the pixel, and the darker shade the end. In the *Signal Inspector* select the `Time` tab to see the beat-cycle for the selected pixel.
- `Force Inspector Settings` panel, `Force` tab contains several options were are explained in detail in *Force Reconstruction Methods*.

#### In-phase and quadrature forces

The `FI FQ` tab brings up a double plot of two integral quantities, plotted versus the **oscillation amplitude** (not static cantilever deflection). The plot $F_I(A)$ is the force which is in-phase with the sinusoidal cantilever motion, integrated over a single oscillation cycle of the cantilever motion. Similarly, the quadrature force $F_Q(A)$ is the force which is 90 degree phase-shifted from the harmonic motion (in phase with the velocity). It is important to note that $F_I(A)$ and $F_Q(A)$ are **not traditional AFM 'force curves'** . They should not be compared to plots of the instantaneous force vs. distance between the tip and surface, or plots of measured cantilever deflection vs. the quasi-static probe height. Every single point on the $F_I(A)$ and $F_Q(A)$ plots, represents an integral of the tip-sruface interaction force over one single oscillation cycle (see *[Platz-2012b]*).

You may notice hysteresis in the $F_I(A)$ and $F_Q(A)$ curves, where the integrated force on the up-beat (increasing amplitude) is different from that on the down-beat (decreasing amplitude). This hysteresis can be the result of several things and it is a subject of on-going research. Some candidate causes are: motion of the cantilever base during the beat caused by over-active feedback (large error signal); excessive noise in the measured intermodulation spectrum; plastic deformation of the surface during the up-beat; strong viscous or inertial forces which delay the recovery of the surface between single oscillation cycles. If the hysteresis is small you can treat it as a weak effect in relation to the overall trend, and in this case smooth single-valued curves can be plotted by selecting `mean curve` in `FI FQ display options`.

#### Conserved and dissipated work

The `Work` tab brings up a double plot very similar to `FI FQ`. The **Conserved Work** is simply $F_I(A) \times A$ and it is that work done by the tip on the surface, which is recovered during the full oscillation cycle, for example due to a purely elastic interaction between the tip and surface. The **Dissipated Work** is similarly $F_Q(A) \times A$ and it represents that work which is lost to heat, or irreversible deformation of the tip and sample.

The plots presented in `FI FQ` and `Work` are **direct transformations of the intermodulation spectral data.** No assumptions about the tip-surface interaction have been made in this analysis. These curves are simply another way of looking at the spectral data.

### Reconstructed force

The `Force` tab brings up a single plot of the effective conservative force vs. **cantilever deflection**. Zero deflection in this plot corresponds to the equilibrium position, and negative deflection to the cantilever bending toward the surface. In order to reconstruct the force some assumptions about the tip-surface interaction must be made. These assumptions and the different reconstruction methods are described on a separate page:

#### Force Reconstruction Methods

Force reconstruction can be performed on individual pixels via the *Force Inspector*, on selected lines in an image by *Analyzing Linear Transects*, or on entire images via *Batch process parameter maps and force volume data*.

ImAFM™ reconstructs tip-surface force $F(d)$ as a function of cantilever deflection $d = z - h$, where the probe height $h$ and the tip position $z$ are measured from a fixed position in the inertial reference frame where the sample is at rest (the lab frame). ImAFM™ force measurement is fast enough such that one can assume constant probe height $h$ at each pixel. This assumption will however break down when the feedback error signal is large and the base is moving rapidly to compensate for a rapid change in surface topography. ImAFM™ makes no assumption about where the surface actually is in relation to the probe height. This is in stark contrast to quasi static force measurement methods, where one must assume a rigid tip and surface when calibrating the measurement of $d$ by moving $h$. In fact, ImAFM™ allows you to unambiguously *define* the location of the surface relative to $h$, by associating it with a distinct feature on the $F(d)$ curve (see *[Forchheimer-2012]*).

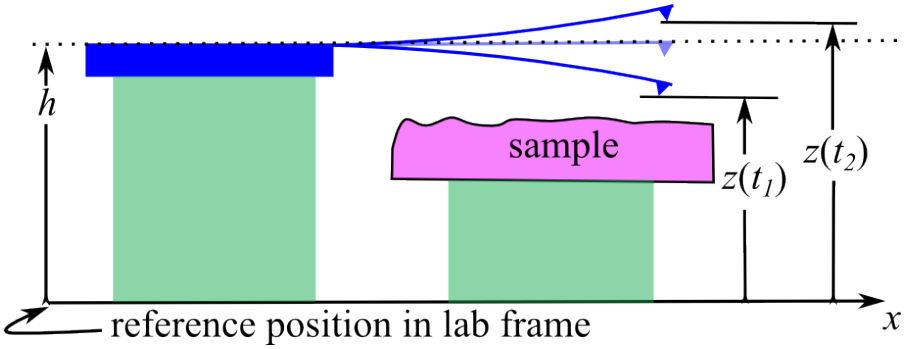



Fig. 3.1: The AFM detector measures cantilever deflection $d$. The probe height $h$ is adjusted while scanning. The tip position in the lab frame is $z = h + d$.

Three basic methods are available for reconstructing $F(d)$.

In the `Force` tab of the `Force inspector settings` panel, check the box to activate the desired `Reconstruction Method`. You can use any combination of methods, and plot all results on the same plot. Each method makes different assumptions described below. Click the method name to highlight it and view the options for that method.

**Polynomial** The `Polynomial` method approximates the conservative tip-surface force (a function of tip-surface separation only) as a polynomial of finite degree $N$ in the cantilever deflection, $d$.

$$F(d) = \sum_{j=1}^{N} g_j d^j$$

A further assumption is that the force is zero when the tip is sufficiently far from the surface. Under these assumptions we can find the $N$ polynomial coefficients $g_j$, both odd and even coefficients, from the measured spectrum of odd-order intermodulation products. The method is described in detail in *[Platz-2012a]*, *[Platz-2013b]*.

`Polynomial` reconstruction has the following options:

- `line style` gives some plotting options for line type and thickness.
- `Maximum IMP order` is largest order of intermodulation product used in the determination of the polynomial coefficients. High order intermodulation products have lower signal level and depending on your scanning conditions, they will disappear into the noise at some maximum order. The maximum order should be set to the largest order IMP, which has a reasonable signal-to-noise ratio (SNR). You can judge the signal the SNR by simply looking for contrast in the amplitude and phase images of any order IMP.
- `Polynomial degree` is the number of coefficients $N$ in the polynomial approximation of the force. This number can not be greater than the maximum order intermodulation product in your spectrum.
- `Assume localized force` check-box activates the routine to determine the even polynomial coefficients. `Zero force region` sets the crossover deflection $d_0$, above which the tip-surface force is assumed to be zero. The range is given in normalized coordinates, where -1.0 means closest to the surface, and +1.0 means furthest from the surface. If you uncheck this fitting option you will reconstruct a force curve which is an odd function of deflection, $F(d < 0) = -F(d > 0)$. The odd nature of the curve is due to the fact that the intermodulation spectrum of odd-order products, is only able to reconstruct the polynomial coefficients, $g_j$ with odd $j$ (see *[Platz-2013b]*). If this odd $F(d)$ curve shows a well developed zero force region for $d > d_0$, then we can safely neglect long-range forces and the assumption that $F(d) = 0$ for $d > d_0$ is well motivated. Move the slider to change $d_0$.

**Model Fit** The `Model Fit` method assumes that the tip surface force is described by a particular interaction model, which has some number of parameters. The method performs a numerical optimization, adjusting the parameters of the model, so as to best reproduce the measured frequency components of the tip-surface force. The method is described in detail in *[Forchheimer-2012]*, *[Forchheimer-2013]*, *[Platz-2012a]*. Nearly any model can be fit to the experimental data, so long as it can be coded on a computer. However, the solver will spit out a solution and the software will give you a plot which looks like your force model - even if it is a lousy fit to your data. Model Fit should always be used together with Polynomial or ADFS, in order to independently check if the model makes sense. Model Fit also requires reasonable initial conditions for the solver to converge to a good solution.

`Model Fit` reconstruction has the following options:

- `line style` gives some plotting options for line type and thickness.
- `Choose model:` selects the different force models that are programed in the software. You can also add your own models to the software, as described in the advanced section on *Programming your own Force Models*. The help icon opens a window showing the functional form, a list of parameters, and plot of $F(d)$ for each model.
- The table gives a listing of the parameters for each model, and the initial value for the numerical solver. If the check-box is unchecked, the solver will not adjust that parameter and it will be fixed at it's initial value.

`Model Fit` can be applied to every pixel in a scan to generate a paramter map, as described in *Batch process parameter maps and force volume data*.

**Amplitude Dependent Force Spectroscopy (ADFS)** `ADFS` makes no assumptions about the particular form of the force curve $F(d)$ other than the force being zero for positive deflection, i.e. $F(d) = 0$ for $d > 0$. The method performs an inverse Able Transform on the $F_I(A)$ curve, to reconstruct the conservative force $F(d)$. The method is described in detail in *[Platz-2012b]* , *[Platz-2013a]*. This method can be applied to create a force volume data set from a scan data file, as described in *Batch process parameter maps and force volume data*.

**Fast Polynomial** A computationally efficient method to determine the polynomial coefficients of the conservative tip-surface force is described in *[Platz-2013b]*. The method is very fast compared to standard *Polynomial* and *Model Fit*. The faster computation enables parameter mapping in real time, as scan data is acquired.

Live parameter mapping availabe as a script the pull-down menue: Advanced -> Scripts -> `LiveParameterMap`.

- `Start` will activate this feature and you can see the selected `Parameter` as a color map, painted during the scan.

- `Show force curve` when activated will plot the polynomial force curve at the center pixel of every scan line. The force plot displays the selected parameter with a line or point on the force curve.

This type of parameter map can also be applied to scan data file, as described in *Batch process parameter maps and force volume data*.

## 3.2 Analyzing lines and surfaces

At one pixel we can analyze data and make a curve of force or interaction energies as a function of cantilever deflection or oscillation amplitude. These curves can be parametrized, for example by fitting the data to a particular model of the interaction force. It is often very interesting to plot how the parameters change along a linear transect of the image. This type of analysis can be made in real time with the *Line inspector tool*. You can also run analysis of all pixels in a scan file to produce a color map image of each parameter. This later analysis is time consuming and it can be run in a batch processing mode. The creation of these different types of parameter plots and maps are described in the following sections:

### 3.2.1 Analyzing Linear Transects

If the *Quantitative Analysis* software is installed, selecting a line with the *Line inspector tool* activated will open the `Line Inspector` panel. You will see a plot the amplitude and phase the intermodulation product corresponding to the image showing when the line was selected. All data in each pixel along the transect line is selected for analysis with the *Model Fit* method of force reconstruction.

- The `Line Inspector` panel gives a list of all selected lines in the left column. The color of the word `line` in the list corresponds to the color of the linear transect in the `Amplitude` and `Phase` images.
- Right-click on the word `line` and choose `Fit model` from the menue. The currently active model will be fit to the intermodulation spectral data along the transect line, and a plot will be generated showing how each parameter of the model changes along the transect. Depending on the length of the line and the speed of your computer, there may be some delay while the fitting is being performed at each pixel.
- You can automatically perform the fitting directly after the line is selected by checking the `Fit model` check box at the bottom of the list of lines.
- `Settings` will open the `Line Inspector Settings` panel where you can activated different force models, specify which parameters to adjust, and set the intial values of all parameters, as described in the *Model Fit* section.
- You can test different models along the same linear transect: Simply change the model in the `Line Inspector Settings` panel, then right-click on the word `line` and choose `Fit Model`. A fresh plot of the parameters of the new force model will be made along this line. A new item is added to the list with each fit that your perform. You can always go back to your previous plots by **double-clicking** on that item in the list.
- Right-click on any an item in the list and chose `Save` to export the results of that fit to a text file. You can also save the plot image by clicking the save icon in the *Image Toolbar*.
- Right-click on any item and select `Remove` to take it away from the list.
- Click on the small triangles to expand and contract the list of fits for each line.
- Right-click on either the `Amplitude` or `Phase` image with the *Line inspector tool* activated to **remove** the line nearest to the right-click.

### 3.2.2 Parameter Maps

You can fit a force model to every pixel of a scan to create a parameter map, or color-coded image of the parameter values. From the `Advanced` pull-down menu, select `Parameter map` to open the `Parameter map creator`. In this panel you may select the `Model` to fit to the data, and the initial values of all parametres, as described in the *Model Fit* section. Because the generation of parameter maps using *Model Fit* is computationally

intensive, it is often easire to use this interface off-line, so as not to overload the computer while scanning. Parameter maps can be generated while scanning using a method based on *Fast Polynomial*. You may PPLY either method to your scan data files from the *Batch process parameter maps and force volume data*, where you can also display the maps as 3D images projected on to the height data.

Analysis is controlled with the following options:

- `scan direction` allows you to choose either the trace or retrace data for analysis.
- `CPU processes` controls how many cores are used when multi-threading the fitting. Fitting a large number of pixels will load the CPU and it may be too sluggish to use while scanning. Adjust this parameter to find a good balance between time-to-output and response time of your computer.
- `X-Y coarse-graining` controls THE number of fits to be performed. If this factor is set to $n$ , fitting will be performed on blocks of $n \times n$ pixels. If it is set to 1, all pixels will be analyzed. Increasing this factor reduces the number of calculations and thus the time to output by a factor $n^2$, and it results coarse-grained map.
- At the bottom is a list file names that are open in the *Analyze Scan Data* view. All checked files will be analyzed, with the same model and initial conditions. The bar below each file indicates the status of the analysis.
- click `Start` to begin the analysis and `Abort` to end the analysis. The results of the analysis (up to the time of Abort) will be saved in the same folder as the scan file that is being analyzed.

When the model fit is performed on a the scan file **scan01234.imp**, several new fiels are created with the same filename. The files **scan01234_p_name.png** are image files with color-coded images of the parameter values. Such a file is created for each parameter **p_name** in your model. The file **scan01234.npz** contains the numerical data of the parameter values stored in one numpy array. This file can be loaded in to a Python script with the numpy function numpy.load(file_name). Here is an example Python script for reading, and replotting the parameter values:

```
# load the npz file in to the object pmap
pmap = np.load('scan01234.npz')
# extract and plot data for parampater 3, vmin and vmax are color bar limits
imshow(pmap['data'][3],vmin=0,vmax=5)
# display the colorbar
plt.colorbar()
```

CHAPTER

FOUR

# ADVANCED TOPICS

In order to comprehend some of the more advanced features in the IMP Suite, it is necessary to understand in more detail how *Intermodulation Measurement* and *Noise Calibration* work. After this general discussion we continue with sections devoted *Programming your own Force Models*. We explain how to use the the *Data Tree* which organizes the analysis and allows you to view spectral data and extract it to an external text file. A section is included on *File Management*, describing the different file types and where they are stored in the computer. We describe how to move and re-arange the different *Panels and Views* and create your own custom screen layout.

Other advanced sections are given for the AFM scientist who wants to experiment with different types of multifrequency measurement and analysis. The IMP Suite has an *Advanced Setup* panel and a *Drive Constructor* to configure the drive tones and measurement frequencies of the Multifrequency lockin Amplifier (MLA) ™. A *Stream Recorder* is also included to record continuous streams of intermodulation data for analysis with your own software. A *Scripting Interface* is also described which allows you to fully customize your multifrequency measurements with scripts that run in the IMP suite. We also document the ScanData python class which organizes the multi-frequncy data. With the functions in ScanData you can write Python scripts that analyze an plot the data stored in the scan files (e.g. scan01234.imp).

## 4.1 Intermodulation Measurement

Intermodulation AFM (ImAFM™) would not be possible without *The Multifrequency Lockin Amplifier MLA™* (also known as the Intermodulation Lockin Analyzer ImMLA™, see *[Tholen-2011]*). The MLA™ comes in different versions and it can be configured in many ways, but a typical configuration for ImAFM™ has the MLA™ is driving the AFM cantilever with two drive tones and analyzing the response at 32 intermodulation products of the two drive tones, such that all frequencies in the response are located close to a high-Q resonance.

Intermodulation response should be zero when the cantilever is oscillating in air above a surface because the freely oscillating cantilever is a linear system. When the cantilever is oscillating close to a surface and the tip is interacting with the surface the cantilever oscillation becomes nonlinear, causing the generation of intermodulation products of the two drive tones. Measuring both the amplitude and phase of the intermodulation products allows one to reconstruct the nonlinearity, or the tip-surface force. Different force reconstruction methods are described in the chapter on *Quantitative Analysis*.

The intermodulation measurement concept can be extended to multiple drive tones and the MLA™ can be configured to drive with more than two tones. A special *Drive Constructor* interface is provided for setting up the multi-frequency drive and configuring the MLA™ to measure at the desired frequencies. Through a process called tuning, the MLA™ and its accompanying software force all drive frequencies to be integer multiples (or very nearly integer multiples) of one base frequency $\Delta f$ and this base frequency serves as a reference signal for lockin measurement of the response. If all the drive tones are integer multiples of the base frequency, all of their intermodulation products will also be at integer multiples of the base frequency.

Such multi-frequency signals are called **frequency combs** because their frequency representation, when plotted as a power spectrum, looks like the teeth of a hair comb, with sharp spectral lines equally separated by the base frequency $\Delta f$. In the time domain the frequency comb is simply a periodic waveform with period $T = 1/\Delta f$. A general statement of the intermodulation measurement concept is the following: Drive a system with a frequency comb and measure a response comb. The nonlinearity can be reconstructed from the difference between the response and drive comb. The underlying assumption is that the response is periodic on the long time scale $T$ associated with the base tone.

The MLA™ has two different modes:

### 4.1.1 Time mode

`Time mode` down samples the response, averaging sequential samples to give an effective lower sampling frequency of. This improves the resolution to 16 bit and it allows for the transfer of every sample to the computer in an uninterrupted stream (see :ref:stream-recorder-label). A DFT of this data stream will give you the entire intermodulation spectrum, up to the Nyquist frequency. This mode reveals all the mixing in your non-linear system. However, the time mode has a latency between the end of the measurement period $T = 1/\Delta f$ and finish of the calculation of the Fourier coefficients, which is the time require to DFT the window of sampled data. Even when using the Fast Fourier Transform (FFT) algorithm to execute the DFT, this latency is too costly when scanning over a surface. In such situations one uses the MLA™ in frequency mode.

### 4.1.2 Frequency mode

`Frequency mode` does the Fourier Analysis of many frequencies in parallel inside the MLA™ as the samples are acquired. In frequency mode you get the full bandwidth of the MLA™ up to the Nyquist frequency set by the sampling freqeuncy of the A/D converters in the MLA. The MLA™ performs $2Y$ Fourier sums in real-time at user-specified frequencies. These sums give you the Fourier cosine and sine coefficients, or the in-phase and quadrature response. This response can be converted to amplitude and phase with some calculation, but often the analysis of data is more conveniently done on complex numbers.

### 4.1.3 Feedback

The MLA™ has a feature specifically designed for AFM, where feedback is required to track the surface when scanning. The amplitude of response at one dedicated feedback frequency is calculated inside the MLA™. This amplitude is subtracted from a set-point amplitude, forming an error signal. A voltage proportional to this error signal is sent to one of the output ports. In order to make the feedback more responsive, the MLA™ updates the error signal 24 times in the measurement period $T = 1/\Delta f$. The sections on *Setup Feedback* and *Drive Constructor* give more information on how the configure the feedback and set-point.

## 4.2 Noise Calibration

A quantitative measurement of tip-surface force requires an accurate calibration of the cantilever. Noise calibration uses the enhanced force sensitivity of a high Q resonance to measure the thermal equilibrium fluctuations of cantilever deflection, and thereby extract the calibration constants of both the cantilever and the detector. The method models the cantilever's free dynamics as a simple harmonic oscillator; an accurate model for one cantilever eigenmode, in a frequency band near resonance.

ImAFM™ also takes advantage of this enhanced sensitivity and high accuracy, using only signals near resonance to reconstruct the force between the tip and the surface. Furthermore, ImAFM™ determines tip-surface force as a function of the cantilever deflection at *fixed probe height*. Thus, both axes of the reconstructed force vs. deflection curve (or force-quadrature vs. amplitude curve) rely on one and the same calibration. Quantitative measurement with ImAFM™ is therefore completely independent of the scanner calibration *[Platz-2012a]* , *[Forchheimer-2012]*. Noise calibration is performed for each cantilever at the start of the ImAFM™ session and it should be redone if any adjustments are made to the detector. Calibration is easily done at any time during a session so it can be frequently redone to check for consistency. Since the accuracy of quantitative ImAFM™ is traceable to this one measurement, it is important to understand the physical ideas behind noise calibration.

Calibration in the field of AFM is traditionally discussed in terms of finding the spring constant $k_s$ associated with the static (independent of time) deflection of the cantilever. Finding this one constant is sufficient to determine a static force $F$, which gives rise to the static deflection $d$,

$$d = \frac{1}{k_s} F$$

ImAFM™ is a dynamic method, where force is determined from cantilever motion $d(t)$. A linear relation between force and motion also exists for dynamic AFM if deflection is small in comparison to the cantilever length. However, due to inertia and damping, the constant of proportionality is frequency dependent.

$$\hat{d}(\omega) = \frac{1}{k}\hat{G}(\omega)\hat{F}(\omega)$$

The frequency dependence is contained in the dimensionless factor $\hat{G}$, called the transfer gain, and the hat denotes an imaginary quantity, with the real part being the Fourier cosine component, and the imaginary part the sine component at the angular frequency $\omega$. The complex, frequency-dependent quantity which relates each frequency component of the force to the component of the motion at the same frequency, is called the linear response function, and it is usually denoted $\hat{\chi}(\omega)$. For the simple harmonic motion of each eigenmode of the cantilever,

$$\hat{\chi}(\omega) = \frac{1}{k}\hat{G}(\omega;\omega_0,Q) = \frac{1}{k}[1 + i\frac{\omega}{\omega_0 Q} - \frac{\omega^2}{\omega_0^2}]^{-1}$$

Three parameters are needed to calibrate each eigenmode: The mode stiffness $k$, resonant frequency $\omega_0 = \sqrt{k/m}$, and the quality factor $Q = \omega_0/\gamma$, or alternatively: the mode stiffness, effective mass $m$ and viscous damping coefficient $m\gamma$, where $2\pi\gamma$ is the width of the resonance in Hz. A complete calibration requires a fourth constant that converts the measured detector signal in Analog-to-Digital Units (ADU) to actual cantilever deflection in nanometers. This fourth constant is called the detector responsivity $\alpha$ [ADU/m].

All four constants can be determined from one thermal noise measurement as described in *[Higgins-2006]*. Here we give a somewhat different derivation of the method which is based on the idea that the cantilever is in thermal equilibrium with the damping medium at temperature $T$, and that the damping can be calculated using hydrodynamic theory. Thermal equilibrium and linear response allow us to use the fluctuation-dissipation theorem to relate the power spectral density of fluctuations of cantilever deflection, to the imaginary part (the dissipative or damping part) of the linear response function.

$$S_{dd}(\omega) = \frac{2k_BT}{\omega}\mathbf{Im}[\hat{\chi}(\omega)] = 2k_BT(m\gamma)\frac{1}{k^2}|\hat{G}(\omega)|^2 \text{ [m}^2\text{/Hz]}$$

The simple harmonic motion gives us the functional form of $|\hat{G}(\omega)|^2$. We fit this function to the measured noise peak at resonance, thus determining $\omega_0$ and $Q$. To get the magnitude of $S_{dd}$ we require knowledge of the damping coefficient $m\gamma$. Hydrodynamic theory and dimensional analysis is used to calculate the damping due to the surrounding fluid (air, water, etc.) *[Sader-1997]*.

$$m\gamma = L\mu \text{ Re } \Lambda(\text{Re})$$

Here $L$ is the length of the cantilever beam and $\Lambda(\text{Re})$ is a dimensionless hydrodynamic function of the Reynolds number,

$$\text{Re} = \frac{\rho b^2 \omega_0}{4\mu}$$

which is a dimensionless combination of the resonant frequency, the fluid density $\rho$ and viscosity $\mu$, and the width of the cantilever $b$ . The hydrodynamic function $\Lambda(\text{Re})$ has been calculated for arbitrary rectangular beams with length much larger than width, $L \gg b$ *[Sader-1998]*. However, the general theory applies to thin cantilevers of arbitrary shape, and $\Lambda(\text{Re})$ has been determined experimentally for the fundamental eigenmode of some commercial cantilevers with non-rectangular shape *[Sader-2012]*.

The deflection noise of the cantilever must be multiplied by the detector responsivity $\alpha$ to convert it to the measured quantity [ADU]. Since the cantilever noise is statistically independent from the detectors own noise, we can simply add their noise powers to get the total noise power spectrum at the output of the detector,

$$S_{\text{tot}}(\omega)[\text{ADU}^2\text{/Hz}] = S_{DD} + \alpha^2 S_{dd}(\omega)$$

We fit this expression to the measured data, with $\alpha$, $\omega_0$, $Q$ and $S_{DD}$ as fitting parameters. Using the value of $\omega_0$ determined from the fit, we can calculate the Reynolds number Re and thereby the hydrodynamic function to determine the damping coefficient $m\gamma$. This coefficient, together with the value of $\omega_0$ and $Q$ determined from the fit, give the mode stiffness $k$. Thus, thermal equilibrium linear response theory and the hydrodynamic damping theory together give us all quantities needed to determine the linear response function of the cantilever and the detector.

It is important to point out that the hydrodynamic damping function, and thereby the theoretical value of the damping coefficient $m\gamma$, depends on the mode shape and is therefore specific to the particular eigenmode. Calculations show that the mode shape of the fundamental eigenmode of a long rectangular beam is particularly insensitive to the Reynolds number. Higher eigenmode shapes are sensitive to Re *[Sader-1998]* and the mass of the tip placed

at the end of the cantilever. This calibration method is therefore applicable to the fundamental eigenmode and we can expect it to be valid in different fluids, but its applicability to higher eigenmodes is questionable.

We should also stress that reconstructing force from the measured deflection over a wide frequency band, for example from many harmonics of a single drive frequency, requires determination of the detector response function $\hat{\alpha}(\omega)$. An ideal detector should have a flat (frequency-independent) response function up to it's cut-off frequency where it it will start to roll-off, or decrease with frequency to some power. However, real detectors do not always behave in this ideal way, and the detector electronics can introduce frequency-dependent amplitude changes and phase shifts over a wide frequency band. Since ImAFM™ works in a narrow band, we escape this difficulty and we can expect accurate calibration and therefore accurate force reconstruction with the assumption of a frequency-independent detector response function.

### 4.2.1 Note on sensitivity and accuracy

In the above text we emphasized that **accuracy** is higher when we base force reconstruction on the callibration of high Q resonance. This notion of accuracy is rooted in physical understanding: We are better able to model the force transducer and deflection detector in a narrow frequency band near a single eigenmode resonance, and thus make a good calibration in this narrow band. We also argued that **sensitivity** is higher near resonance. Our notion of sensitivity is independent of that regarding accuracy and it does not originate from theoretical understanding of the physics of cantilever beams or opto-electronic detection. Sensitivity has to do with the signal-to-noise ratio ($SNR$) of *measurement*.

The field of AFM has unfortunately adopted the term 'inverse optical lever sensitivity' (or invOLS) to describe the constant $\alpha^{-1}$ which converts the measured detector signal (e.g. Volts) to nm of cantilever deflection. We use the term **responsivity** for $\alpha$ because it is actually the magnitude of a linear response function, and it does not tell us anything about the $SNR$ of the measurement. The sensitivity of the measurement is described by two quantities which are displayed in the `Calibration Result` panel.

`Thermal noise force` is the random force due to collisions of the molecules in the damping fluid with the cantilever. This random force has zero average value but the average of the force squared is not zero. The thermal noise force is the square root of the power spectral density of force fluctuations $\sqrt{S_{FF}(\omega)}[\text{fN}/\sqrt{\text{Hz}}]$. The force noise power spectrum is independent of frequency, $S_{FF} = 2k_BT(m\gamma)$ and this type of 'white noise' arises whenever the damping force is simply proportional to velocity. With this thermal noise force we can calculate a **minimum detectable force** $F_{\text{min}}$, or the force measured with $SNR = 1$ in a given measurement time $T$ (measurement bandwidth $B = 1/T$).

For example: The scan speed and image resolution dictate a pixel time of $T = 1$ ms, and the thermal noise force is $\sqrt{S_{FF}} = 22$ fN$/\sqrt{\text{Hz}}$. The minimum detectable force at each pixel is therefore $F_{\text{min}} = \sqrt{S_{FF}B} = 696$ fN. This minimum force is the 'signal' which just equals the noise. A good measurement is typically characterized by a signal which is many times the noise level, or $SNR \gg 1$. Note that you must scan 4 times more slowly to decrease $F_{\text{min}}$ by a factor of 2.

The detector `Noise floor` is the second quantitative measure of sensitivity. If the measurement time is short or if you measure at frequencies away from the high-Q resonance, $SNR$ is typically not determined by the actual force noise of the cantilever in its damping medium, but rather by the electronic noise of the detector, $S_{DD}$. We express this detector noise as an *equivalent* deflection noise by dividing it with the detector responsivity, $\sqrt{S_{dd}^{\text{equiv}}} = \alpha^{-1}\sqrt{S_{DD}}$. Here again we assume that the detector noise is independent of frequency in the band of interest. If the pixel time is $T = 1$ ms and $\sqrt{S_{dd}^{\text{equiv}}} = 150$ fm$/\sqrt{\text{Hz}}$, the minimum detectable cantilever deflection at each pixel would be, $d_{\text{min}} = \sqrt{S_{dd}^{\text{equiv}}B} = 4.7$ pm.

It is also interesting to express the detector noise as an `Equivalent force` noise $\sqrt{S_{FF}^{\text{equiv}}} = k\sqrt{S_{dd}^{\text{equiv}}}$. For the example given above and $k = 40$ N/m, we find $\sqrt{S_{FF}^{\text{equiv}}} = 6$ pN$/\sqrt{\text{Hz}}$ , which, in a measurement time $T = 1$ ms gives an equivalent minimum detectable force of $F_{\text{min}}^{\text{equiv}} = kd_{\text{min}} = 0.19$ nN. This would be the minimum detectable force with the cantilever if the measurement were dominated by detector noise, as is often the case for quasi-static force measurements.

Thus, sensitivity of the measurement is characterized by two quantities: The noise force of the cantilever, which represents a fundamental limit, and the noise of the detector. One would like the detector noise to be as low as

possible and a very useful way to compare different detectors is to use the ImAFM™ system to perform thermal noise calibration on the same cantilever mounted in two different host AFMs. Since the cantilever force noise is identical in each case, we can compare the ratio of the thermal noise peak, to the detector background noise, or the `Peak to flat ratio`. The larger this ratio, the better your detection. It is also interesting to track this number as you measure. If this ratio becomes smaller, it may mean that the detector is poorly adjusted, or there may be some additional source of detector noise.

## 4.3 Programming your own Force Models

One powerful feature of ImAFM™ is the ability to test different tip-surface interaction models on the same data set. Data is stored as the raw intermodulation spectrum at each pixel, which is a frequency-domain representation of the tip motion. The *Model Fit* section of *Force Reconstruction Methods* describes how to use the IMP Suite to fit this data to an a force model. This fit can be done at an individual pixel (see *Force Inspector*) , along a liner transect (see *Analyzing Linear Transects*), or on an entire image (see *Parameter Maps* and *Three dimensional viewer*). Several common force models are programed in the IMP Suite, and it is very easy to program your own force model and have it appear in the IMP Suite.

Constructing a good and physically well motivated force model can be difficult. However, once you have a good force model, programing it in the IMP Suite is simple. Some knowledge of the Python language is necessary (see Python). Simply copy the **examples.py** file and give it a new name, e.g. **my_force_model.py** , keeping it in the **force_models** folder. Edit the copy to create your own force model. The **example.py** file is well documented with comment lines to help you understand the idea behind the Python code.

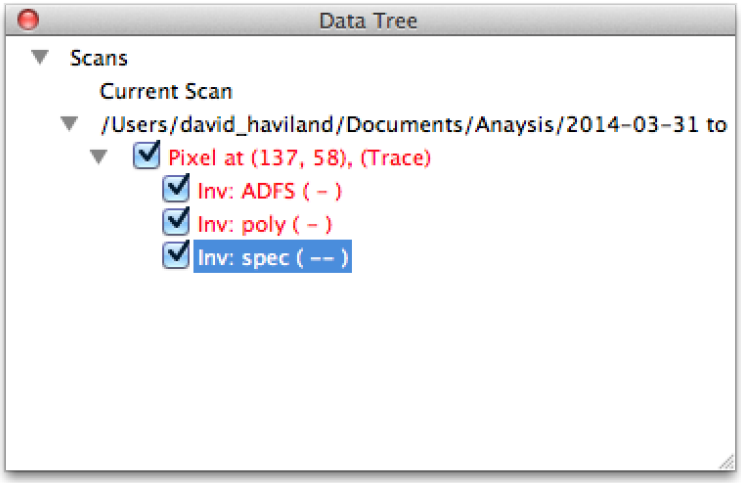
After you have finished with **my_force_model.py**, restart the IMP Suite. Your force model will be automatically loaded and it will appear as an option in the `Model` pull-down menu. Note that any changes you may have made to the **examples.py** file will not be saved, and upon restart, it will be returned to its original, default state.

## 4.4 Data Tree

The `Data Tree` panel is available from the `Advanced` pull-down menu. The panel can be docked in either the scanning view or the analysis view, or both. This panel lists scans which are open in the analysis panel as well as the current scan. Under each scan there is a list of all the pixels which have been selected with the *Pixel inspector tool*. The color of the text for each pixel corresponds to the color of the cross marking the pixel in the image. Under each pixel there is a list of the different force reconstructions done on that pixel.

**Right click on a scan file name** and select:

- `Open shell here...` to open a Python shell with an object called `image` containing all the data stored in this scan file. The data id of the scan used by the data tree is given, along with a couple of useful commands. The shell is for advanced users who will need the developer documentation to use this feature effectively.
- `Get calibration` to open a dialog box with the calibration data stored with this scan file, or the *Current calibration* at the time that the data file was closed.




- `Save as ascii ...` to open a dialog box where you can save all amplitude and phase data in ASCII format. The save will create individual files in a new, empty folder. There will be one file for both amplitude and phase at each of the measured frequencies, both trace and retrace. For example, when 32 frequencies are measured, 128 data files will be created. If the image is 256 x 256 pixels, this corresponds to about 140Mbytes of data in tab-delimited text, with a carriage return at the end of each scan line.

  The name of each file begins with a number which codes for the frequency. The number corresponds to the index of the 'k-array' which stores the integers multiples of $\Delta f$ which give the frequency values where amplitude and phase is measured (see *Intermodulation Measurement*). In the folder there is also a file called *metadata.txt* which contains a list of integers in the array *LO_IMP_KARRAY*. The number at the beginning of each file corresponds to the index of this array (zero being the first element). The integer values stored in this array, times *LO_DELTA_F*, gives the frequency at which the amplitude and phase is measured.

**Right click on a pixel** and select:

- `Open shell here...` to open a Python shell with an object called `pixel` containing the data relevant to this pixel. The data id used by the data tree is given, along with a couple of useful commands. The shell is for advanced users who will need the developer documentation to use this feature effectively.
- `Delete` removes the pixel from the data tree. The cross will also be removed from the image, and the plots from the Fore Inspector panel. You can also remove any pixel by right-clicking close to that pixel in the image when the *Pixel inspector tool* is selected.
- `Save time data to text file` to export the cantilever deflection vs. time during the time window for this pixel. This data is is actually the inverse FFT of the spectral data taken by the MLA™, with some zero padding to give appropriate sampling in the time domain.
- `Save spectrum data to text file` to export create the raw spectral data measured by the MLA™ at this pixel.
- `Save FI FQ data to text file` to export the FI(A) and FQ(A) data for this pixel (see *In-phase and quadrature forces*).

The check-boxes at each pixel and each force reconstruction controls plotting. Un-check to remove the cross from the image or plot from the Force Inspector panel, without actually removing the data from the data tree. Checking the box will show the plots again.

Pixels selected in the current scan will not be removed when a new scan is generated. When the scan moves passed a selected pixel, the image no longer corresponds to the selected pixel. Selected pixels must be removed manually in the current scan.

`Clear All` in the `Force Inspector` panel removes all selected pixels in all scans.

**Right click on a force reconstruction** and select:

- `Open shell here...` to open a python shell with an object called `force` containing the result of the force reconstruction at this pixel. The data id used by the data tree is given, along with a couple of useful

commands. The shell is for advanced users who will need the developer documentation to use this feature effectively.

- `Get fitted parameters` to open a dialog box showing the fitted parameters when the *Model Fit* method is used.
- `Save Data to text file` to export the force curve found using that reconstruction method.

## 4.5 Advanced Setup

The `Advanced Setup` view is initially selected in the `Advanced` pull-down menu. Thereafter the icon appears on the right column, below the work flow icons. Selecting `Advanced Setup` again will uncheck the selection and hide the icon. In this view you can control the drive for standard Intermodulation AFM using two drive tones, set the feedback, and measure the response in real time.

`Requested` fields are the desired, or target values of:

- `f1 [kHz]` the frequency of drive 1
- `f2 [kHz]` the frequency of drive 2
- `df` the measurement bandwidth, df = abs(f2-f1) / n, where n = 1,2,3...
- `A1 [%]` the amplitude of drive 1, in percent of full output
- `A2 [%]` the amplitude of drive 2, in percent of full output

`Actual` show the values that you get, which depends on which algorithm you choose for frequency tuning.

### 4.5.1 Frequency tuning

Frequency tuning is key to performing measurmenets with the **Multifrequency Lockin Amplifier (MLA)**™ (MLA™). Tuning is the process of selecting the base tone **df** and the actual drive tones, so that they meet the criteria for ImAFM™; that all frequencies are integer multiples **df** (see *Intermodulation Measurement*). There are three different algorithms for tuning:

- `None` takes the requested frequencies and does not tune them at all. Without tuning, multi-frequency linear response will be corrupted by Fourier leakage between drive tones and it is not possible to get an accurate measurement of intermodulation.
- `Rounding` selects the closest frequencies to the requested values, such that all frequencies will be near-integer multiples of one base frequency. Rounding gives a very small amount of Fourier leakage between tones, but in almost all cases this leakage is well below the dynamic range of the measurement, and therefore considered negligible. The phase error is corrected at the end of each measurement time (T=1/df), so there should be no noticeable phase drift. With this algorithm there is considerable freedom in the choice of frequencies.
- `Integer` is a more strict algorithm, where the condition of integer multiples is met exactly. This algorithm gives no Fourier leakage between tones and no phase error, but it is more restrictive in the choice of the possible values of df. You should use this algorithm when the MLA™ is synchronized to external frequency generators. To avoid phase drift, you should make sure that the frequency of the external generator is an exact integer multiple of **df** given in the IMP Suite, to as many significant figures as possible with your generator.

The exact properties of these different tuning options have to do with the way in which frequencies are synthesized and analyzed in the MLA™ which we do not discuss in detail here. It suffices to say that the small errors induced in

the **Rounding** algorithm are negligible for ImAFM™, and we recommend that you use this tuning. The automatic setup uses this algorithm.

### 4.5.2 Setup Feedback

Before you engage a sample, and after you have made any changes to the drive configuration, you must setup the feedback. Feedback for ImAFM™ is controlled by the amplitude of response at one of the frequencies measured by the MLA™ (see *Feedback* section). For the basic two-frequency drive, feedback is run at frequency **f1**. With the *Drive Constructor* you have more control over which frequency to set as the feedback frequency.

- `Setup` will adjust the feedback so that zero volts at the feedback output port corresponds to the given set-point.
- `Set-point` is the desired response amplitude, given as a percentage of the free response amplitude. Adjusting the set-point to more than 100% will cause the probe to lift away from the surface. If you change the set-point by a large amount, for example from 95% to less than 50%, it is a good idea to re-run `Setup` feedback. The new set-point values are active as soon as they are entered in the field, and you hit return (or tab).

The feedback port sends out an error signal for PID control of the Z-scanner. This feedback error signal is put back in to the host AFM controller, in the place of the cantilever deflection signal. If the host AFM is set to contact mode with the feedback set-point in the AFM software set at zero volts, the AFM's PID control will adjust the Z piezo to keep the error signal at zero volts, or the value of the set-amplitude. The feedback gains are adjusted in the host AFM which is actually performing the feedback, using the error signal is calculated by the MLA™.

For example: If the set-point is set to 85%, the system will engage the sample until the response amplitude at the feedback frequency drops to 85% of its free value. When this 85% condition is met, the MLA™ will have zero volts at the feedback output. In our experience this amplitude feedback scheme is sufficient for tracking most surfaces. When scanning large areas on rough surfaces, the feedback has to respond rapidly in order to track the surface, and rapid adjustments of the cantilever base height are necessary. Force measurement is very difficult when the cantilever base is rapidly accelerated by an over-active feedback. This acceleration gives rise to additional forces on the tip which are not taken in to account in the reconstruction algorithms. Hence overactive feedback means inaccurate force measurement. Improving feedback and actually incorporating the feedback signal in to the force reconstruction is a subject for future research and development.

### 4.5.3 Measure

You can measure and plot the response in real time using two different modes:

- `Run time mode` starts the measurement of the response in the *Time mode*, and plots the sampled stream of data in the time domain and its discrete Fourier transform (DFT) in the frequency domain. The discrete data is plotted with a connected blue line. You will notice a jumping of the phase of the oscillation envelope in the time-domain signal. This is normal as the data are analyzed and plotted in asynchronous chunks, and not as one continuous stream. The DFT of the time-sampled data is however stable as each chunk as the same sampling frequency and same number of samples.
- `Run freq. mode` starts the measurement of the response in the *Frequency mode* and plots the amplitude at the measured frequencies (vertical red bars) in the frequency domain, and the oscillation envelope in the time domain (connected red lines)
- `Stop` will terminate the measurement. You must stop the measurement before you start other measurements, for example scanning a sample or taking stream data.

### 4.5.4 Units

You can select between displaying the cantilever response signal in Analog-to-Digital Units `ADU` , or in nanometers `nm`. You must have a *Current calibration* in order to display in nanometers.

### 4.5.5 Out of Range Error

The MLA™ is designed to handle signals within a 'normal range' for a 'typical AFM'. Depending on your AFM and our experiment, these normal range settings may need to be adjusted.

When the **input signal** exceeds the maximum, 'clipping' occurs inside the MLA™ and this induces harmonic and intermodulation distortion in the spectrum. One way to avoid this problem is to simply attenuate the input signal. Intermodulation Products provides attenuators to place at the SIGNAL IN port for this purpose. Note however that a large signal coming from an AFM detector may bring the detector close to saturation, which also gives harmonic and intermodluation distortion of the spectrum. Furthermore, a cantilever will behave with a nonlinear restoring force when it is driven to very large response amplitude. One should be careful not to confuse these sources of nonlinearity, which result in harmonic and intermodulation distortion of the free cantilever oscillation, with harmonic and intermodulation due to a tip-surface force.

The **output signal** should also not exceed the maximum or be too small, in order to avoid distortion in the MLA™. The requested drive amplitudes `A1 [%]` and `A2 [%]` are given in percent of full output (the actual values are give in Digital-to-Analog units). The drive waveform coming from SIGNAL OUT port of the MLA™ can be conditioned with external amplifiers or attenuators to suit the application. Intermal adjustments can be made inside the MLA™ to give more or less output voltage. Contact Intermodulation Products regarding these adjustments.

## 4.6 Drive Constructor

The multiple tones in a frequency comb represent a periodic waveform in the time domain. The Drive Constructor interface lets you configure the Mutifrequency Lockin Analyzer MLA™, creating the drive comb and choosing the measurement frequencies. If you have a version of the MLA™ with more than two drive tones, for example the IMP-24-24, there are endless possibilities for different drive waveforms and the question of which drive waveform is optimal for a particular measurements is the subject of ongoing research. Before attempting to use the Drive Constructor, you should read the section on *Intermodulation Measurement*.

The MLA™ versions are denoted IMP-X-Y, and they are constructed such that the X drive tones always overlap with the and Y frequencies where response is measured. In other words, response is always measured at the X drive frequencies and $X \leq Y$. If you have the IMP-24-24 you can work with up to 24 frequencies which are the same on both the drive and response sides. You can always work with fewer frequencies on the drive side by simply setting the drive amplitude to zero at any drive frequency, thereby only measuring response at this frequency.

### 4.6.1 Constructing a drive frequency comb

A Python scripting interface is built in to the drive constructor to help in the construction of drive frequency combs. Using the interface requires knowledge of the Python programming language. A pull-down menu lists the name of various Python scripts, stored in **impdata/drive_setups/user_drive_scripts.py**. These scripts are well commented to help you understand how they work. You create a new script by changing the name of an old script, and pressing `Save`. Similarly, `Delete` will kill the currently selected script.

The scripting interface has some useful functionality:

- Change font size with ctrl+Plus / ctrl+Minus or ctrl+Mouse wheel.
- Hit ctrl+Space for a list of reserved keywords
- A quick help and link to this manual appears by clicking the IMP help icon .

#### Pre-defined variables

The following variables are defined in all scripts:

- **f0** [Hz] and **Q** are the measured resonant frequency and quality factor stored in the *Current calibration*.
- **nfreq_out** and **nfreq_in** are the number of drive frequencies and response frequencies respectively. These numbers will depend on the MLA™ firmware that you are running.
- **f_sample** is the sampling frequency [samples per second] of the MLA™.

#### Built-in functions

The following built-in functions are provided in all scripts:

- **tune_integer(df)** takes one argument, the target value of **df** . It returns a re-defined value of **df** that is commensurate with divisions of the MLA™ clock frequency, such that Fourier coefficients will be calculated for perfect integer multiples of **df**. This function is equivalent to the `integer` button in the frequency-tuning controls of *Advanced Setup*. You should use this tuning if you are synchronizing the MLA™ with other instruments.
- **tune_round(df, f0)** takes two arguments, the target value of **df** and a desired frequency commensurate with **df** (e.g. the resonant frequency of the cantilever) . It returns a re-defined value of **df** such that Fourier coefficients will be calculated for near-integer multiples of **df**. This function is equivalent to the `round` button in the frequency-tuning controls of *Advanced Setup*.

#### Required quantities

The script must set the values of the following variables:

- One (and only one) of the following which specifies the measurement bandwidth: Either **df** [Hz], **T** [sec], or **samples_per_pixel** [integer]. **(df = 1/T = samples_per_pixel/f_sample)**.
- An array of integers **n** giving the frequencies for both drive and response. The length of the array **n** must be **nfreq_in** and the first **nfreq_out** entries are the drive frequencies. Alternatively, you can specify the frequencies in an array called **f**. Set either **n** or **f**, but not both. **(f=n*df)**.
- A real array **a** with the amplitude of all drive tones. The length of the array **a** must be **nfreq_in**. Amplitudes are given in DAU (digital-to-analog units). A helping function **max_ampl()** is useful in setting the amplitude.
- A real array **p** with the phases of all drive tones. The length of the array **p** must be **nfreq_out**. Phases are given in radians.
- A real number **asf** between zero and one. This amplitude scaling factor will set the peak amplitude of drive signal. **asf = 1** corresponds to maximum output voltage of the MLA™. The default value that you get if you do not specify this variable is **asf = 0.1**. An error will appear in the debug window if **asf** is out of the range [0,1]. **asf = -1** it overrides this function (advanced users only!).

### 4.6.2 Synthesize and Configure

`Synthesize Comb` runs the script and plots the comb, as an amplitude-phase plot in the frequency domain, and the waveform in the time domain. The MLA™ can be configured with this comb in one of two ways:

`Configure Drive` causes a voltage signal described by the synthesized frequency comb to be put at the **signal out** port of the MLA™.

`Configure Response` adjusts the comb at the **signal out** port, such that the synthesized comb appears at the **signal in** port. If the input signal is the detector of an AFM measuring the deflection of a cantilever the actual cantilever motion will be that given by synthesized frequency comb. Configure Response assumes that a chain of linear systems (actuator -> cantilever -> detector) is connected between the output and input ports of the MLA™ and it will not work properly when nonlinearity is present.

### 4.6.3 Debugging a script

The `Debug` window allows you to test what is happening with your script. Error messages will appear in this window and you can print any variable here using the **dprint(var_name)** statement in your script. The script automatically prints relevant data for your comb in the Debug window.

### 4.6.4 Setting the feedback frequency

By convention, the MLA™ calculates the feedback error signal from the amplitude of the response at the frequency located in the zeroth position of the **n** array (or **f** array). You should make sure that your script puts the frequency at which you would like to run feedback in the zero position the **n** array. Note that the arrays do not need to be sorted in any particular order, for example from lowest to highest frequency, but there must be a one-to-one correspondence between the elements of the arrays which set the frequencies (**n** array), amplitudes (**a** array) and phases (**p** array).

More information on feedback can be found in the section on *Intermodulation Measurement* (*Feedback*) and in the section on *Advanced Setup* (*Setup Feedback*).

### 4.6.5 Useful Python code blocks

Some useful blocks of code for making frequency combs are described below. These code blocks are used in the example scripts. You can copy and paste these in to your scripts.

Tune **df** close to 500 Hz and set the frequencies to consecutive integer multiples of **df**, centered as close as possible to the resonant frequency **f0**:

```
df = tune_integer(500)
f1 =f0 - (nfreq_out / 2) * df #start freq of comb
n1 = round(f1/df) # integer  closest f1
n = np.int_(arange(nfreq_out) + n1) # integer array of frequencies
```

Tune **df** closer to 500 Hz and set the frequencies to consecutive integer multiples of **df**, centered as close as possible to the resonant frequency **f0**:

```
df = tune_round(500,f0)
f1 =f0 - (nfreq_out / 2) * df #start freq of comb
n1 = round(f1/df) # integer closest f1
n = np.int_(arange(nfreq_out) + n1) # integer array of frequencies
```

Exchange the frequency with the index **mi**, with the feedback frequency at position **n[0]**:

```
#put frequency near resonance as first frequency for feedback
mi=nfreq_out/2 #index of center of comb
n[mi], n[0], a[mi], a[0], p[mi], p[0] = n[0], n[mi], a[0], a[mi], p[0], p[mi]
```

Create an signal in the time domain, consisting of a rapidly oscillating component at the frequency **f_bar** and a slowly modulated amplitude **mod**. Fourier transform and pick out the **nfreq_out** components close to **f_bar** and set the amplitudes *a* and phases *p*:

```
N=2*int(2.*f_bar/df) #number of time samples, so f_max = 2*f_bar
t = arange(0.,1,1./N)/df
#construct signal x(t) in the time domain and FFT to get comb
mod = 0.1*sin(2.*pi*arange(N)/N) # the modulation function
x =(1.+ mod)*cos(2.*pi*f_bar*t) # x(t)
x_hat = fft.rfft(x)
# take components of comb, at frequencies given by n array
a = abs(x_hat[n])
asf = 0.1 # adjust peak amplitude
p = angle(x_hat[n])
```

Create an signal in the time domain, consisting of a rapidly oscillating component with a slowly modulated frequency **f_bar*mod(t)** . Fourier transform and pick out the **nfreq_out** components close to the center frequency **f_bar** and set the amplitudes *a* and phases *p*:

```
N=2*int(2.*n_bar) #number of time samples, so f_max = 2*f_bar
t = (1./df)*arange(0.,1,1./N)
#construct signal x(t) in the time domains
x = cos(2. * pi * ( f_bar * t   -   delta_f /(4*pi*df)*sin(2*pi*df*t)))
# FFT to get frequency comb
x_hat = fft.rfft(x)/(N/2.)
a = abs(x_hat[n])
asf = 0.1 # adjust peak amplitude
p = angle(x_hat[n])
```

## 4.7 Stream Recorder

When scanning a sample, the MLA™ process end-of-line (EOL) and end-of-file (EOF) triggers and lockin data is stored at pixel locations in a scan file. The stream recorder ignores all triggers and stores data as one continuous, uninterrupted stream. This mode is quite useful for taking data when the AFM probe slowly approachs and retracts from a surface. The data stream can be stored in either time mode or frequency mode (see *Intermodulation Measurement*).

- `Start` will start the stream record. Click again to `Stop`. If the *Autosave* box is checked in the *Status Banner*, each run of the stream recorder will result in a file being saved in the session folder. The file name has the form **record01234** where the number is automatically incremented. In *Time mode* the files will have the **.std** extension, and in *Frequency mode* the files will have the **.imp** extension (see the *File Management* section for more information on file types). Unchecking the `Autosave` box will result in no data being saved.
- `Mode` selects weather the data is stored in *Time mode* or *Frequency mode*. In either mode all data is saved as a continuous stream without any breaks or gaps in the data.
- `Plot` controls only which data is being plotted and does not effect the saving of data. You can adjust the number of points to be plotted in the past number of seconds. The check boxes enable plotting of the amplitudes (or amplitude and phase in the polar plot) at the different frequencies listed.

Note that in the *Time mode* the response at all frequencies in the comb can be examined by analyzing stream data with the Fast Fourier Transform. A script called *PlotTimeMode* (see *Scripting Interface*) is provided which gives a simple GUI inteface for plotting and extracting time-mode data taken with the stream recorder. Below we give an example which can be a useful starting point for your own analysis scripts. The script can be copied to a new filename.py, modified and run, for example in the iPython shell.

### 4.7.1 Example script

This script reads a time-mode stream data file (.std file) and parses it in to time windows or 'beats', on which the signal is periodic. Each time window is assigned an index (the beat index) and the terminal asks for the beat index on which you want to perform analysis. The script extracts that beat from the data file, and simply plots both time data and the frequency data. Note that you must input the path to the IMP Suite on your computer, and the path to the .std file that you want to analyze:

```
import matplotlib.pyplot as plt
import numpy as np
import sys
```

```
# Path to IMP Suite
suitepath = '/Users/david_haviland/IntermodulatorSuite'
sys.path.append(suitepath)
from StreamRecorder import stdfile

# Path to stream recorder file in time-mode
recorder_path = 'path_to_file.std' # full path to recorder file in .std format
print "loading file", recorder_path
sf   = stdfile.stdfile(recorder_path,b_raw=False,do_scale=False)

# Read metadata from file
fs = sf.freq_samples # Sampling frequency, Hz
f1 = sf.f1 # First drive frequency, Hz
f2 = sf.f2 # Second drive frequency, Hz

# Calculate number of samples to avoid Fourier leakage
n_samples_beat = int(np.round(fs/abs(f2-f1))) # Number of samples in one beat
t = 1./fs*np.arange(n_samples_beat) # Time axis for plotting
df = fs/n_samples_beat # Frequency resolution
freqs = df*np.arange(n_samples_beat/2+1) # Frequency axis for plotting

# Index each beat in the stream
ii_s = np.arange(0,sf.n_samples,n_samples_beat)[:-1] # remove last since it might not be complete

# Loop through all beats and read max value
beats_to_plot = 1000
if len(ii_s)<=beats_to_plot:
    ii_plot = ii_s
else:
    skip = float(len(ii_s))/beats_to_plot
    ii_plot = np.int_(skip*np.arange(beats_to_plot))

peak = np.zeros(len(ii_plot))
for i,beat_i in enumerate(ii_plot):
    if i%100==0:
        print "Beat %i / %i"%(beat_i, len(ii_s))
    # Read data
    i_start = ii_s[beat_i]
    data = sf.get_samples(i_start,n_samples_beat)
    peak[i] = max(data)

# Plot
plt.figure(1)
plt.clf()
plt.plot(ii_plot,peak)
plt.xlabel("Beat index")
plt.ylabel("Peak value [ADU]")
plt.show()

# Ask terminal for beat number, then data from that beat
n = -1
while n == -1:
    s = raw_input("Enter beat index to plot: ")
    try:
        n = int(s)
    except ValueError:
        print "Input must be an interger"

data = sf.get_samples(ii_s[n],n_samples_beat)
data_fft = np.fft.rfft(data)/len(data)

# Plot
```

```
plt.figure(2)
plt.subplot(211)
plt.plot(t,data)
plt.xlabel("Time [s]")
plt.ylabel("In [ADU]")
plt.subplot(212)
plt.semilogy(freqs*1e-3,2*abs(data_fft))
plt.xlabel("Frequency [kHz]")
plt.ylabel("Amplitude [ADU]")
plt.show()
```

## 4.8 Scripting Interface

The IMP Suite comes with a python scripting interface with which you can develop you own multifrequency AFM methods and customize the IMP Suite to your particular measurement needs. From this interface you can access all the classes and functions used by the IMP Suite for data acquisition, storage, plotting, and analysis. To take full advantage of the possibilities that this interface allows and to develop your own measurements, you will need to learn the Python programing language, and become familiar with the structure and functionality of the IMP Suite as described in the developer documentation.

Intermodulation Products provides a variety of scripts which can be modified and saved with a new name. All scripts stored in the folder **IMP_sessions_and_settings/settings/scripts** will be loaded when the IMP Suite starts, and they will appear in **Advanced** pull-down menu under **Scripts**. To run the script, simply select it from the menu. `Reload scripts` will close all open scripts are reload the currently saved script.

The file **Examples.py** contains several different classes, each containing a script with different functionality. These scripts demonstrate how to make a GUI or step a quantity while scanning. You can expand on these scripts to add GUI elements and controls, or simply edit the values in the Python code, reload the script, and run it. These scripts serve as a starting point to develop your own measurement methods.

Some useful scripts currently available are:

### 4.8.1 RecorderAnalysis.py

`PlotTimeMode` opens a GUI for viewing and extracting sections of a *Stream Recorder* file. Run the script, press `Open` and select a previously recorded **.std** file containing stream data taken in *Time mode*. The script will parse the time stream to a series of 'beats' , or time windows $T$ given by the inverse of the measurement bandwidth $T = 1/\Delta f$, assigning a 'beat index' to each window. A plot shows the maximum value of the oscillation envelope in each beat. You can adjust the time window to include more than one beat, thereby reducing the measurement bandwidth and thus the noise. The time window is shown in the lower plot. `Export All` will export the entire recorder file and `Export zoom` will export only the selected window (lower plot) to an ASCII format file. A Fast Fourier Transform (e.g. FFT) of this data will give the response spectrum at the selected time window.

### 4.8.2 LiveParampeterMap.py

`LiveParameterMap` runs an experimental new method for extracting polynomial force curves which is computationally very efficient, so that the curves are analyzed and parameter maps are made in real time, as the AFM scans. The method was developed and implemented by Daniel Forchheimer, starting from a theory worked out by Daniel Platz *[Platz-2013b]*. Choosing this script opens a GUI which allows you to choose ways of parameterizing the conservative tip-surface interaction force. A map of these parameters is created in real time and a force curve showing the extracted parameter can be plotted. The force curve is taken at one location (center) of the fast-scan axis and the plot is updated at the line frequency.

## 4.9 Scan Data

The IMP Software Suite stores data from a scan, including all relevant metadata, in one compact file with the file extension .imp (e.g. scan01234.imp). The **ScanData** class manages the storage and retrival of the data. If you want to write your own Python scripts to analyize multifrequency data taken with the IMP Software Suite, you will need to use the **ScanData** class. The documentation below was auto generated from the doc strings in Python code at the time this manual was compiled. You can always see the documentation of the actual class version that you are using in the Python code itself, using auto-complete with any good Python API (Advanced Programming Interface).

### 4.9.1 Using the ScanData class

Below are some example scripts which demonstrate how to load the ScanData class and get at the data stored in the scan file.

Can we make some kind of structure like matplot lib to exand tp see soruce code or result of run?

example of how to imshow the phase of particular frequency.

example of how to exchange the free oscillation with a particular pixel.

### 4.9.2 ScanData Class

**class** Scanner.ScanData.**ScanData**(*args=[]*)

Handels the storage and retreval of data from the scan file (e.g. scan01234.imp).

This class is designed to be easily extendable and new functions will be added as the IMP Suite grows.

**Most functions in this class fall in to one of two groups:**

- Use *append_* and *reset_* to prefix functions for managing data in a list.

Use when you want to save the history which changes during the scan. The final member of the list is often called the 'current' data. *append_* function adds to the end of a list. *reset_* function clears the list to length zero and adds a new initial element.

- Use *get_* and *set_* to prefix functions which get data and set data respecitvely in the ScanData class.

This can be the raw image data at any pixel, or meta data such as the calibration or free oscillation.

**To Do:**

- clean our not used functions.
- change invOLS to invOLR everywhere

**append_lo_change_linenrs**(*val*)

Append the list of change_linenrs values

**append_lo_delta_f**(*val*)

Append the list of delta f values

**append_lo_drive_amplitudes**(*ar*)

Append the list of drive_amplitudes

**append_lo_drive_karray**(*ar*)

Append the list of drive_karray values

**append_lo_drive_phases**(*ar*)

Append the list of drive_phases

**append_lo_feedback**(*ar*)

Append the list of feedback

**append_lo_free_oscillations**(*ar*)
Append the list of free_oscillation

**append_lo_imp_karray**(*ar*)
Append the list of imp_karray values

**append_lo_samples_per_pixel**(*val*)
Append the list of samples_per_pixel values

**append_lo_sampling_freqs**(*val*)
Append the list of sampling_freq values

**append_lo_scan_rates**(*val*)
Append the list of scan_rate values

**append_lo_tip_Vac**(*val*)
Append the list of tip AC voltage values

**append_lo_tip_Vdc**(*val*)
Append the list of tip DC offset values

**append_setpoint**(*setpoint*, *linenr=-3*)
Append a setpoint to the setpoint history.

The optional linenumer argument can also be negative linenr = -1 : changed in last image linenr = -2 : during setup linenr = -3 : unknown point of time

**equal_array**(*ar1*, *ar2*)
Checks to see if two arrays have equal length.

**Parameters**

- **ar1** – np.array
- **ar2** – np.array

**Returns** True or False

**Return type** bool

**get_Q**()

**Returns** dimensionless quality factor.

**Return type** float64 [-]

**get_change_linenr**()
Return the current value of change_linenrs, i.e. the last in the list

**get_delta_f**()
Return the current value of delta f, i.e. the last in the list

**get_drive_amplitudes**()
return the current (i.e. latest) drive amplitudes

**get_drive_karray**()
Return the current value of drive_karray, i.e. the last in the list

**get_drive_phases**()
return the current (i.e. latest) drive phases

**get_external_filename**()

**get_feedback**()
Return the current value of feedback, i.e. the last in the list

**get_free_oscillation**()
Return the current value of free_oscillation, i.e. the last in the list

**get_free_oscillations_complex**(*num=-1*)

**get_imp_karray**()
Return the current value of imp_karray, i.e. the last in the list

**get_imp_str_list**(*mode=-1*)
Returns a list of imp strings, containing e.g. 'Drive1', 'Drive2', 'IMP3L' etc. Without further options, the strings are returned as saved in the corresponding ImageData. With mode = 0, same as mode==-1, but if strings are empty automatically mode 2 With mode = 1, same as mode==-1, but if strings are empty automatically mode 3 With mode = 2, strings of the imp-ks are returned, e.g. 'k = 345'. With mode = 3, strings as defined in ScannerPanel are returned, depending on the lockin scheme.

**get_internal_imp_str_list**()

**get_invOLS**()

**Returns** resopnsivity of optical lever.

**Return type** float64 [nm/ADU]

**get_k**()

**Returns** catilever eigenmode stiffness.

**Return type** float64 [N/m]

**get_loaded_filename**()
Filename that was used when loading the ScanData from disk

**get_lockin_scheme**()
Gets the lockin scheme used for scanning, currently returning 0, 1 or 2

**get_metadata_ascii**()
Return all metadata as a string new-line separated string

Strategy for all following data entries: IDENTIFIER[UNIT]: DATA

**get_original_filename**()

**get_p_detector_white**()

**Returns** ???what is detector white

**Return type** float64 [???]

**get_p_thermal**()

**Returns** ??? what is p_thermal

**Return type** float64 [???]

**get_params_dict**()

**get_resolution**()

**get_resonance_frequency**()

**Returns** resonance frequency

**Return type** float64 [Hz]

**get_samples_per_pixel**()
Return the current value of samples_per_pixel, i.e. the last in the list

**get_sampling_freq**()
Return the current value of sampling_freq, i.e. the last in the list

**get_scan_rate**()
Return the current value of scan_rate, i.e. the last in the list

**get_scan_size_x**()

**Returns** scan size in the fast-scan direction x.

**Return type** float64 [meters]

**Note:** The scan size is determined by the host AFM and must have been entered in manually in the IMP suite. Automatic reading for some AFM's is under development.

**get_scan_size_y**()

**Returns** scan size in the slow-scan direction y.

**Return type** (float64) [meters]

**Note:** The scan size is determined by the host AFM and must have been entered in manually in the IMP suite. Automatic reading for some AFM's is under development.

**get_setpoint**()
Return the current value of setpoint, i.e. the last in the list

The linenumber of the setpoint chnage is not returned.

**get_starttime**()

**get_tip_Vac**()
Return the current value of tip AC voltage, i.e. the last in the list

**get_tip_Vdc**()
Return the current value of tip DC offset, i.e. the last in the list

**given_list_is_empty**(*lst*)
Returns True if list is [] or only has elements of type '', otherwise returns False

**has_calibration**()

**has_equal_params**(*other*)

**isEqual**(*other*)

**load_from_file**(*filename*)

**load_h5_file**(*filename*)

**load_legacy_imp_file**(*filename*)
Loads data from binary file in .imp format

**purge_parameters**()
Purges the parameter history lists.

All except for the last entries are removed from the parameter lists. This is useful when a new image is saved then the parameter history of the previous image should be removed. Only the last value in each list is kept as the initial parameter for the new image.

**reset_lo_change_linenrs**(*val*)
Reset the list of change_linenrs values and initialize it with one element with value val

**reset_lo_delta_f**(*val*)
Reset the list of delta f values and initialize it with one element with value val

**reset_lo_drive_amplitudes**(*ar*)
Reset the list of feedback values and initialize it with one element with array ar

**reset_lo_drive_karray**(*ar*)
Reset the list of drive_karray values and initialize it with one element with karray ar

**reset_lo_drive_phases**(*ar*)
Reset the list of feedback values and initialize it with one element with array ar

**reset_lo_feedback**(*ar*)
Reset the list of feedback values and initialize it with one element with array ar

**reset_lo_free_oscillations**(*ar*)
Reset the list of free_oscillation values and initialize it with one element with array ar

**reset_lo_imp_karray** (*val*)
Reset the list of imp_karray values and initialize it with one karray ar

**reset_lo_samples_per_pixel** (*val*)
Reset the list of samples_per_pixel values and initialize it with one element with value val

**reset_lo_sampling_freqs** (*val*)
Reset the list of sampling_freq values and initialize it with one element with value val

**reset_lo_scan_rates** (*val*)
Reset the list of scan_rate values and initialize it with one element with value val

**reset_lo_setpoints** (*val*)
Reset the list setpoints values and initialize it with one element, a value val

**reset_lo_tip_Vac** (*val*)
Reset the list of tip AC voltage values and initialize it with one element with value val

**reset_lo_tip_Vdc** (*val*)
Reset the list of tip DC offset values and initialize it with one element with value val

**save_to_ascii** (*filename=None*)
Export to a collection of generically named ascii-files in the directory 'dirname'.

Creates a separate subdirectory for the scan and separate files for each amplitude and phase image for easy import into Matlab or similar.

If dirname==None (default) the directory is automatically named after the scanData file

**save_to_file** (*filename*)

**save_to_h5** (*filename*)

**save_to_legacy_imp_file** (*filename*)
Saves data as binary file in .imp format

**set_Q** (*Q*)

**Parameters** **Q** – float64 [-] dimensionless quality factor.

**set_calibration_flexural** (*kwargs*)

**set_calibration_torsional** (*kwargs*)

**set_change_linenr** (*val*)
Set the current value of change_linenr, i.e. the last in the list, to new a new value val

**set_delta_f** (*val*)
Set the current value of delta_f, i.e. the last in the list, to new a new value val

**set_drive_amplitudes** (*ar*)
resets the list of drive amplitudes and appends the given array

**set_drive_karray** (*ar*)
Set the current value of drive_karray, i.e. the last in the list, to a new karray ar

**set_drive_phases** (*ar*)
resets the list of drive phases and appends the given array

**set_external_filename** (*str*)

**set_feedback** (*ar*)
Set the current value of feedback, i.e. the last in the list, to new a new array ar

**set_free_oscillation** (*ar*)
Set the current value of free_oscillation, i.e. the last in the list, to new a new array ar

**set_imp_karray** (*ar*)
Set the current value of imp_karray, i.e. the last in the list, to new a new karray ar

**set_invOLS** (*invOLS*)

**Parameters** **invOLS** – float64 [nm/ADU] responsivity of optical lever.

**set_k**(*k*)

**Parameters** **k** – float64 [N/m] cantilever eigen mode stiffness.

**set_nr_drive_freqs**(*nr*)

**set_original_filename**(*str*)

**set_p_detector_white**(*p_detector_white*)

**Parameters** **p_detector_white** – float64 [???] ???what is detector white

**set_p_thermal**(*p_thermal*)

**Parameters** **p_thermal** – float64 [???] ???what is p_thermal

**set_resolution**(*i_x*, *i_y*)

**set_resonance_frequency**(*f0*)

**Parameters** **f0** – float64 [Hz] resonance frequency.

**set_samples_per_pixel**(*val*)
Set the current value of samples_per_pixel, i.e. the last in the list, to new a new value val

**set_sampling_freq**(*val*)
Set the current value of sampling_freq, i.e. the last in the list, to new a new value val

**set_scan_rate**(*val*)
Set the current value of scan_rate, i.e. the last in the list, to new a new value val

**set_scan_size_x**(*value*)

**Parameters** **value** – float64 [meters] scan size in the fast-scan direction x

**set_scan_size_y**(*value*)

**Parameters** **value** – float64 [meters] scan size in the slow-scan diretion y.

**set_starttime**(*val*)

**set_tip_Vac**(*val*)
Set the current value of tip AC voltage, i.e. the last in the list, to new a new value val

**set_tip_Vdc**(*val*)
Set the current value of tip DC offset, i.e. the last in the list, to new a new value val

**swap_calibration_parameters**()

## 4.10 File Management

The IMP suite is kept in different places, depending on your computer system. In Windows, it is installed in **c://Program Files/IntermodulatorSuite**. Users do not need to care about this folder as it contains only static files which should be installed from an installer. All dynamic files that are changed when you change settings in the IMP Suite, store data, save a script, etc., are stored in the folder **c://IMP sessions and settings**. This folder has the following sub-folders:

**Moving data to another computer**

To transport your data to another computer for analysis, be sure to first import the host AFM data (i.e. height image data) in to your session folder using the *Session Overview*. Then simply copy the entire session folder to another computer with the IMP Suite installed. When you perform analysis on another computer, all newly created analysis files will be added to the session folder.

**/sessions** This folder contains session folders. Each time you start the IMP Suite a dialog box opens to create a new, or add to an existing session folder. The default name of the new session folder is the date, but you have the option to append a session name to the date. When Autosave is checked (see *Status Banner*), data is automatically stored in the session folder: scan files, calibration files, stream files, the session log, etc.. When you analyze data to create new files or import host AFM data files, the default behavior is to always store everything in the session folder.

**/settings** This folder contains many files that are changed dynamically by the IMP Suite and configuration files for different AFMs. Normal users do not need to work directly with these files but advanced users may want to modify them. If these files become corrupt, they can be discarded and the IMP Suite will automatically recreate the files with their default values on the next start of the IMP Suite. The settings folder has several sub-folders:

**/calibration** Contains several text files with the calibration constants for each type of cantilever programmed in the IMP Suite, including those created by a user. There is also a file **fluid.txt** containing the density and viscosity of the various fluids that you may want to work in.

**/configurations** Contains files for configuring the IMP Suite to work with your particular host AFM. The normal user will not need to be concerned with these files.

**/drive_setups** Contains the file **user_drive_setups.py** which is a Python file containing the scripts for the *Drive Constructor*, both example scripts and user-constructed scripts.

**/force_models** Contains Python files with the force models. You can add your own force model files here by copying and modifying **/example.py**. When you restart the IMP Suite this file will be re-loaded and your model will appear as a new force model.

**/scripts** Contains Python scripts which can be sued to control different measurement schemes and create different modes. This is for advanced users who will require some knowledge of the basic Python objects in the IMP Suite. A few examples are given in **/Examples.py**

**/config.ini** This is the main configuration file which is dynamically changed by the IMP Suite. The normal user will not need to be concerned with this file. If it becomes corrupted, it can be deleted and a new file will be created with default values upon restart of the IMP Suite.

### 4.10.1 File Types

The IMP Suite generates files with a name indicating the type of file, followed by an automatically incremented 5-digit counting number (denoted '01234' below). You are free to append an underscore followed by any valid file text **after** this counting number (e.g. scan01234_my-file-text.imp). You may experience problems keeping track of your files if you remove or modify this number or the type name before it. The following files are generated by the IMP Suite and stored in a session folder:

- **calib01234.txt** noise data and fitted calibration parameters (see *Calibration*).
- **calib01234.png** image of plot in calibration view.
- **sweep01234.txt** frequency sweep data (see *Frequency Sweep*).
- **sweep01234.png** image of the frequency sweep plot.
- **scan01234.imp** data for one scan, including the current calibration, in HDF5 format.
- **recorder01234.imp** continuous stream of data taken in frequency mode (see *Stream Recorder*).
- **recorder01234.std** continuous stream of data taken in time mode.
- **scan01234_model.npz** parameter map data for the fitted **model** (see *Parameter Maps*).
- **scan01234_p-name.png** color map image of the parameter **p-name**.
- **sessionlog.txt** chronological session log (see *Session Logbook*).

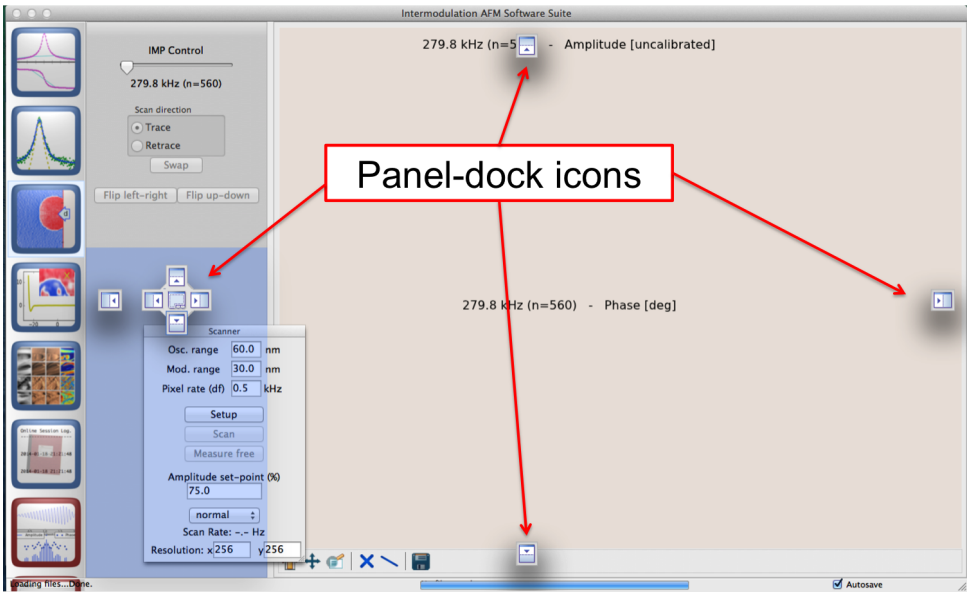
You can always export an image of any plot that you see on screen by clicking the save image icon in the *Image Toolbar*, which will bring up a save dialog box with several file format options. You can also export raw data and the results of analysis to a text file using the *Data Tree* .

## 4.11 Panels and Views

All views, or screen layouts, have a main panel to which auxiliary panels can be docked. Several views are pre-defined and they appear when clicking icons in the left column symbolizing the *The Work Flow*. Icons for the advanced panels appear when selected in the `advanced` pull-down menu. To removed the advanced icons, select again in the pull-down menu.

Different panels appear when you click `Settings` buttons, or they can be chosen from the `Analysis` pull-down menu. You can add these panels to the views, or rearrange the panels in a view according to your desire. Movable panels have a shaded grab-bar on top, where the panel name is located. These panels can be free-floating, or you can dock them to a particular view.

- To un-dock a panel, click-and-drag the panel bar. Release when it is un-docked and it will be free-floating. A double-click on the panel bar will also un-dock the panel.
- To dock a panel, click-and-drag the panel bar of a free-floating panel and panel position icons will appear. Move your mouse cursor to the desired dock location on the icon, and your screen will show a shaded area. Upon release the panel will dock to the shaded area.



CHAPTER

FIVE

# INSTALLATION

## 5.1 Install Software

The IMP Software Suite is installed with a standard installer. When you install the software, you agree to the terms of the IMP license. The IMP software Suite can be run on the same computer as the host AFM, or on a separate computer. It is advantageous to run the IMP Suite on a modern computer with a multi-core processor, especially when analyzing full images to make *Parameter Maps*.

If the IMP Suite does not detect the The Multifrequency Lockin Analyzer™ (MLA™) upon starting, it will open up in analysis mode. In analysis mode you can plot and analyze data taken previously, but you can not take data. You are free to install the software on as many seperate computers needed to analyze your data. To take data you mast start the IMP Suite when connected to the MLA™ and a host AFM, as described below.

## 5.2 Install Hardware

Connecting the hardware the first time requires some effort. However, if things are configured nicely, one or two hardware switches is all that is needed to switch between the normal configuration of your host AFM and the ImAFM™ configuration. The MLA™ is connected to the host AFM via a signal access module (SAM) provide by Intermodulation Products or your AFM supplier. The MLA™ is connected to a computer running the IMP Suite via Ethernet, either the same computer used by the host AFM, or a seperate computer.

### 5.2.1 Connection to computer

The IMP Suite will open analysis mode when it does not detect an MLA™ connected to the computer. To establish the connection between the computer and the MLA™ you must first perform the steps below. After this procedure the detection will be automatic. The instructions given below are for **Windows 7**.

1. Connect a standard Ethernet cable between the MLA™ and the computer.
2. Go to `Control Panel` -> `Network and Internet` -> `Network and Sharing Center`.
3. **Locate the network adapter:** In the left panel choose `Change adapter settings`. To identify which adapter corresponds to the Ethernet card connected to the MLA™, turn off the MLA™. There should be a red cross on the adapter icon with the text `Network cable unplugged`. About one minute after the MLA™ is turned on the red cross will disappear and the text changes to `Unidentified network`.
4. **Configure the MLA adapter:** Right click again on the MLA adapter and choose `Properties`. Select `Internet Protocol Version 4 (TCP/IPV4)` and click `Properties`. Click `Use the following IP address` and fill in the following

   **IP address: 192.168.42.1**

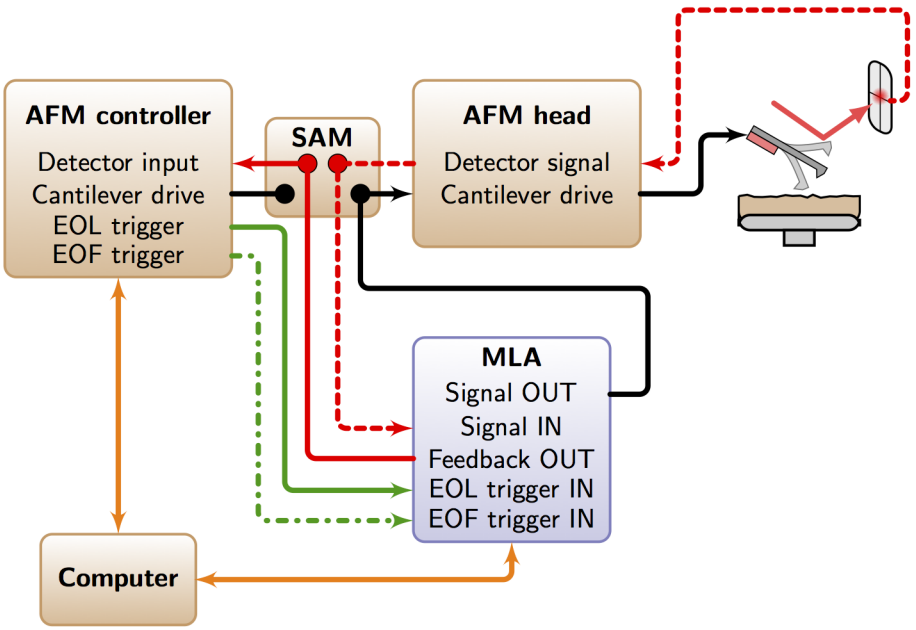
   **Subnet mask: 255.255.255.0**

5. **Check the adapter:** At this point the internet connection between the MLA™ and the computer should be established. To test the connection you can ping the MLA™. In a Windows terminal window type `ping 192.168.42.50`. The MLA™ should respond with something like:

Pinging 192.168.42.50 with 32 bytes of data:

Reply from 192.168.42.50: bytes=32 time=1ms TTL=128

### 5.2.2 Connection to host AFM




The general connection scheme is shown the diagram above. The cantilever drive, detector, feedback and trigger signals must be routed through the MLA™. This routuing may be with with BNC cables to the font pannel of the MLA™, or with a composite cable to the **AUX** connection of the back panel of the MLA™. On some AFMs a separate Signal Access Module (SAM) is required. Intermodulation Products provides dedicated SAMs for a few common AFMs to easily toggle between the normal function of your host AFM and ImAFM™. On other AFMs, notably Asylum and JPK, one connects BNC cables directly to the controller and changes signal routing using software activated switches. You can get a script from Intermodulation Products to automatically perform the signal routing. Detailed instructions are given below for different AFM's. Contact **Intermodulation Products** to find out what solutions exist for your particular AFM <info@intermodulation-products.com>.

## 5.3 Set AFM Type

In the IMP Suite, under the `Advanced` pull-down menu, select `Setup AFM`. A dialog box appears with a pull-down menu to choose your AFM type. This option will only appear when the IMP Suite detects the MLA™ and starts in full mode, ready for taking data. The settings for the various AFM types are stored in the folder **IMP Sessions and Settings/settings/configurations**. These files contain information about triggers, over-scan factors, and more. Advanced users can use the files in this folder as a template to make their own **custom_afm.ini** settings file. When the software is restarted, a new **custom_afm** settings will appear as a choice in the pull-down menu.

If your AFM type does not have a configuration file, contact **Intermodulation Products** for help in making a custom configuration file <info@intermodulation-products.com>.

### 5.3.1 Working without triggers

Nearly all AFM's have some kind of access to the end-of-frame (EOF) and end-of-line (EOL) triggers. If the EOF trigger does not exist, it is still possible to manually start the ImAFM™ scan when the host AFM scan starts. However, after several scans a manual restart is needed to re-sync the frames. If the EOL trigger does not exist,

it is also possible perform ImAFM™ but in this case one needs to accurately adjust the timing in order to keep ImAFM™ in sync with the host AFM.

Under the `Advanced` pull-down menu, select `Setup AFM`. Two fields appear in the AFM Setup dialog. The `Line frequency` should be set to the frequency at which you want 'fake' EOL trigger signals to come. The `Delay` is the number of pixel time intervals the MLA™ will wait after the 'fake' EOL trigger, before it starts to record a scan line. Setting both of these fields to zero causes no 'fake' EOL signal to be generated, and in this case the IMP Suite relies on the trigger signals recived by MLA™. These two fields should be set to zero when running with external triggers from the host AFM.

## 5.4 Common AFMs

### 5.4.1 Nanoscope ™ III, IIIa, IV

ImAFM™ works perfectly well with older Multimode and Dimension AFMs, originally developed by Digital Instruments (DI), then sold by Veeco and currently by Bruker. These are excellent AFM's and there are many good instruments still in service. The upgrade to ImAFM™ is a good way to give these systems a second life and convert them to a modern AFM with the latest surface analysis capabilities. You do not need to upgrade to a NS-V controller and ImAFM™ performance is not compromised with the older NS-III and NS-IV controllers.

Access to the detector signal and cantilever drive are provided via a Signal Access Module (SAM) from Intermodulation Products. This gives you low noise and low cross-talk connection with the host AFM and one switch is all that is required to toggle between normal use of your AFM and ImAFM™. The SAM should be placed in between the microscope and the controller. If there is a Phase Extender Module with the NSIIIa controllers, you should place the SAM in between the microscope and the phase extender module. A general rule of thumb is: Place the SAM directly after the microscope, before the controller or any other ancillary equipment.

You can also use the SAM provided by DI/Veeco/Bruker, which gives access to many other signals, but has some cross-talk between signals which degrades performance, and it requires two switches to change between normal operation and ImAFM™. The actual connections on the DI/Veeco/Bruker SAM depend on which version you have, and which controller you are running. Consult your DI/Veeco/Bruker manual when making these connections. Contact Intermodulation Products if you have any troubles as we have found errors in some versions of these manuals. See *SAM III connections* for an image showing a typical connection.

The trigger signals on the NS-IV controller are accessible from BNC connectors on the back side of the controller. On the NS-III and NS-IIIa controllers they are accessible via BNC connectors located inside the controller box. You need to remove the lid to access these connections. If you would like a more clean solution, you can install connectors on the front of the controller. You need to remove the front panel and drill two holes for this installation. Intermodulation Products can provide the necessary cables and advice.

See *Nanoscope III and IIIa Trigger Access* for images and detailed instructions on accessing the trigger signals.

### 5.4.2 Nanoscope ™ V

The NS-V controller is currently sold by Bruker for most of their AFMs e.g the Icon and Fast-Scan AFMs. If the NS-V is running a Multimode AFM, or Dimension AFM, the IMP-NS4-SAM gives you signal access. If the NS-V controller is running on a Multimode or Dimension AFM, you can use the same SAM as that for the NSIII and NSIV controller described above. If you are running a Bruker Icon, Fast-Scan, or other more recent AFM using the NSV controller, **Intermodulation Products** has a low noise SAM with access the vertical and latteral detector signals, as well as apply a voltage to the tip. If these connections are sufficient, you do not need the SAM-V module from Bruker. However, if you have the SAM-V, you can use it to make the connections. See *Nanoscope V Connections* for an image showing a typical connection. Contact Intermodulation Products if you would like a dedicated ImAFM™ SAM for the NS-V Icon or Fast-Scan systems.

Access to the trigger signals is on the front panel of the NS-IV controller. See *Nanoscope V Connections* for an image showing the access to the trigger signals.

### 5.4.3 Asylum MFP-3D ™

These systems can be found with the older MFP-3D ™ controller, the ARC ™ and ARC2 ™ controller. With all of these controllers, signal access is via BNC connections on the front panel of the controller, and signal routing is configured in the software cross-point switch.

**Hardware connections:**

- **OUT A** on the MLA™ <-> **In 1** on the controller.
- **OUT 1** on the MLA™ <-> **In 0** on the controller.
- **IN 1** on the MLA™ <-> **Out 0** on the controller.

**Cross-point connections are most easily made by running a script, or Igor Procedure file ImAFM_MFP3D.ipf supplied by I**

- **user.alias.l** (left column) <-> **Deflection** (right column).
- **user.alias.d** (left column) <-> **Input.fast** (right column).
- It is necessary to **write** the changes and **Lock** the cross-point
- You can **Read** the changes in the **All** tab and check if **Deflection** is indeed connected to **Input.fast**.
- NOTE: making these changes redefines the alias's for all modes, and therefore Contact mode will not work as normal unless you switch back to the original settings, or restart the Asylum software. Make a note of what **Deflection** is set to before you make these changes manually.

The trigger connections require that you purchase a controller accessory from Asylum Research called the Digital Access Module ™ (DAM). This module connects to a DIN connector on the front of the controller, it has BNC connections for:

- **Port 2 LINE** on the DAM <-> **TRIG 1** on the MLA™.
- **Port 3 FRAME** on the DAM <-> **TRIG 2** on the MLA™.

### 5.4.4 Asylum Cypher ™

The Cypher AFM runs the ARC or ARC2 controller. The signal connections can be made as with the MFP-3D, but it is preferable if they are made on the so-called 'backpack' of the Cypher itself. The signal connections are:

- **Output 0** on the Cypher backpack <-> **IN 1** on the MLA™.
- **Input 0** on the Cypher backpack <-> **OUT 1** on the MLA™.
- **Input 1** on the Cypher backpack <-> **OUT A** on the MLA™.

The trigger connections with the ARC and ARC2 controller are done exactly as with the MFP-3D controller, via the Digital Access Module ™.

### 5.4.5 JPK Nanowizard ™ III

The connections to the JPK Nanowizard III are shown here: *JPK Nanowizard III Connections*.

As with other systems, ImAFM™ is done with the JPK software in contact mode. Run the IMP-JPK script to open a small GUI which aids in setting all parameters in the JPK software. Press `Setup` to make the JPK system ready for ImAFM™. Note that when doing the noise calibration on a JPK system, it is a good idea to turn off the high voltage to the Z piezo. Press the button `HV-Z OFF` to toggle on and off the high voltage.

### 5.4.6 NanoTec Electronica

As with other systems, you should set the Nanotec software to run contact mode. In the DA (data acquisition) view, set all other modes to “no” in the Scanning->Scan Options panel.

The Nanotec Dulcinea SPM controller has various inputs and outputs which have to be configured in the Nanotech WSxM Software. Please note that the cantilever drive signal output from the MLA™ requires a special connector at the AFM head or a specific signal routing in the Nanotech Dulcinea controller. Please contact Nanotec for further details.

The signal in port of the MLA™ has to be connected to the BNC port C on the front side of the Dulcinea controller. In the WXsM software, open the Dulcinea BNC monitor and set “C (800 kHz)” to “Normal force” in order to output the cantilever deflection signal.

The feedback signal generated by the MLA™ is put into channel 7 on the rear side of the controller. Open the feedback panel in the WXsM software (View -> Feedback) and set the Feedback Channel to CH 7. Set the the setpoint in the scan control panel to 0 V.

To configure the trigger signals open the User Digital Signals panel (View -> Digital Signals) and choose the configuration “<Customize....>”. Set channel 0 to “Image” and channel 3 to “X ramp”. Now, the Dulcinea controller outputs an EOF trigger on channel 0 and an EOL trigger on channel 3 at the digital signals connector at the rear side of the controller. Please note, that channel 0 corresponds to pin 2 and channel 3 to pin 9 on the connector.

Before starting to scan, the voltage offset of the feedback channel 7 has to be adjusted. Proceed in the ImAFM™ work flow until you have setup the piezo drive and the feedback my clicking on Setup in the Scanner Panel. Now, open the Input menu in the WxSM software (View -> Inputs), select the tab for channel 7 and click on “Tune offset”. If the signal in the scope view of channel 7 is now at 0 V, the tip can be engaged. Make sure that there is no offset filter active when looking at channel 7 in the WXsM software.

#### Hardware Connection images

##### SAM III connections

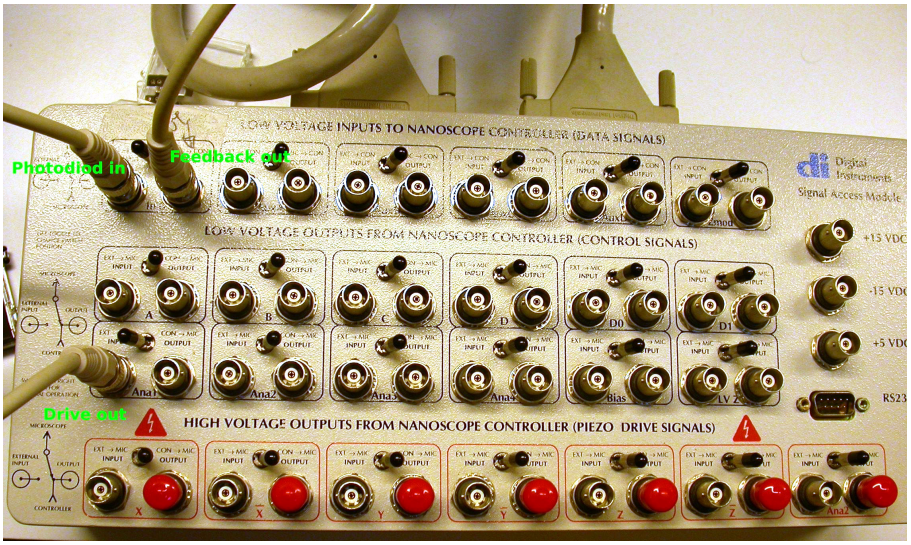

Photodiod in
Feedback out
LOW VOLTAGE INPUTS TO NANOSCOPE CONTROLLER (DATA SIGNALS)
LOW VOLTAGE OUTPUTS FROM NANOSCOPE CONTROLLER (CONTROL SIGNALS)
Drive out
HIGH VOLTAGE OUTPUTS FROM NANOSCOPE CONTROLLER (PIEZO DRIVE SIGNALS)

Fig. 5.1: Typical connections for the SAM from Veeco/Digital Instruments. The images shows the SAM III, connected to a Dimension 3100 AFM. These connections may be different, depending on the controller, AFM, and SAM versions. The switches in the image are in the position for ImAFM™ (left for ImAFM™, right for normal AFM).

### Nanoscope III and IIIa Trigger Access

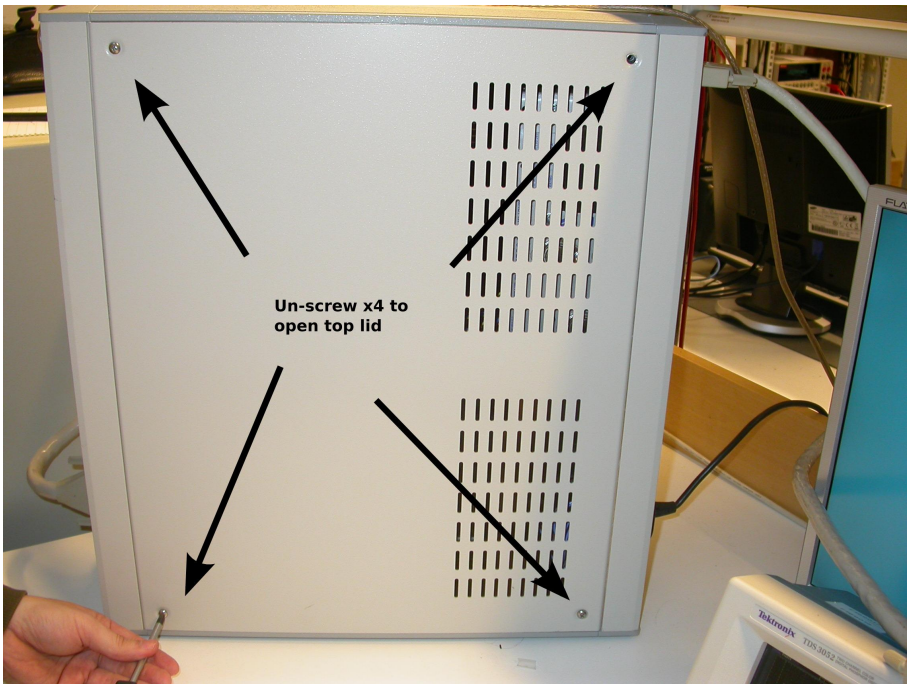



Fig. 5.2: Remove the 4 screws in each corner of the lid on the NS-III or NS-IIIa controler.

### Nanoscope V Connections

### JPK Nanowizard III Connections

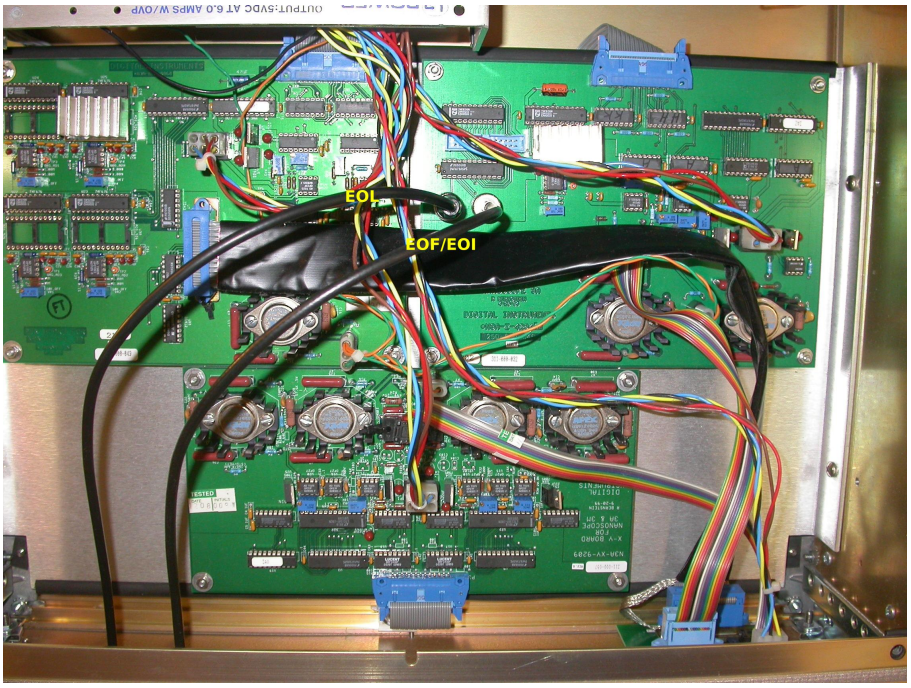



Fig. 5.3: Connect the End of Line (EOL) and End of Frame (EOF) triggers to the BNC connectors on the circuit board as shown. The images shows cables which bring the these connections to BNC bulk-head connectors mounted on the front panel of the controler.

Fig. 5.4: BNC bulk-head connectors giving access to EOL and EOF connectors on the front panel.

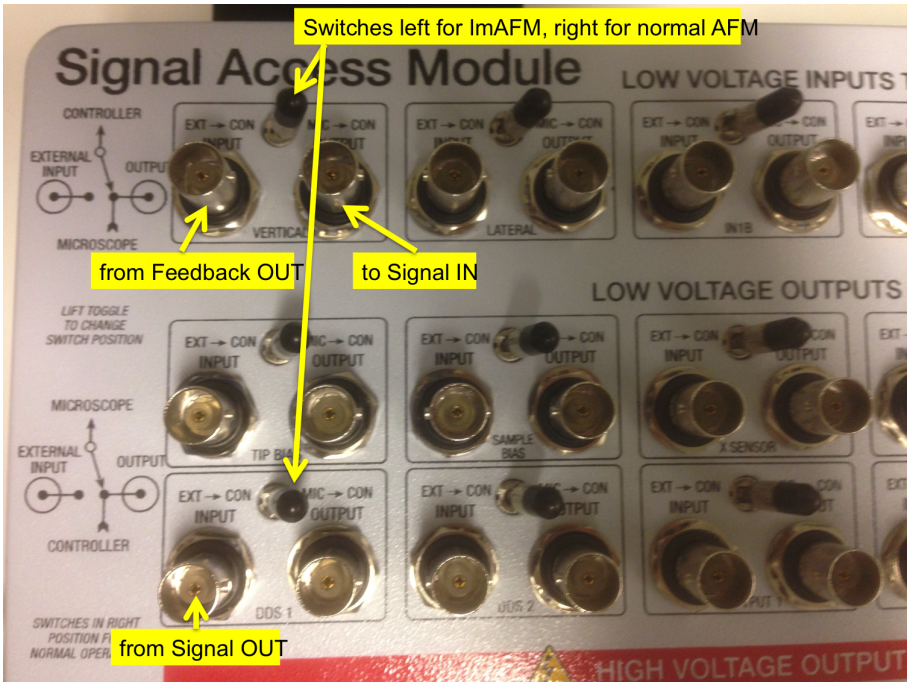



Fig. 5.5: The connections to the SAM-V from Bruker are identical to the SAM modules from DI and Veeco. However, these SAM modules can not be used interchangably.

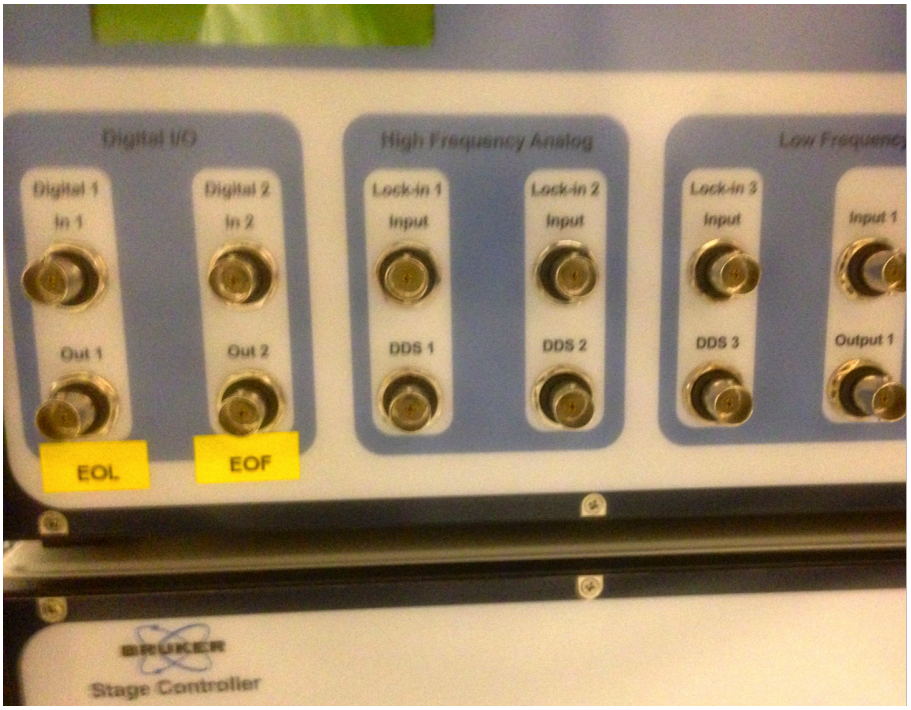
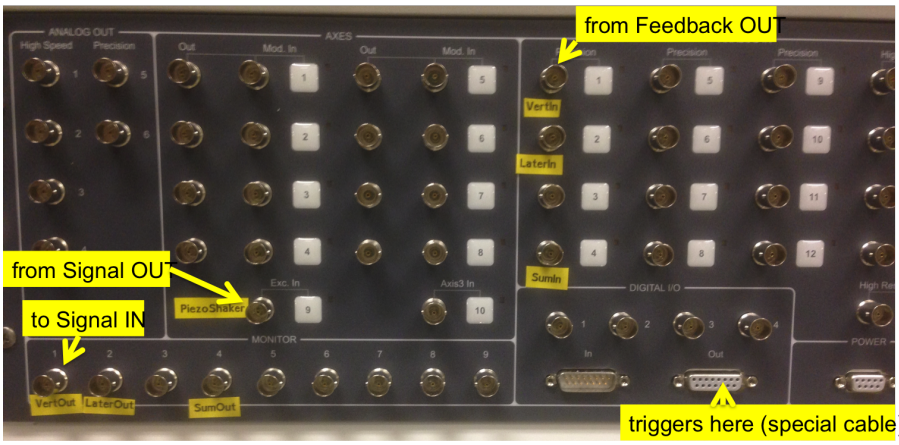



Fig. 5.6: The EOL and EOF triggers are on the front of the NS-V controller. Make the connections as labeled in the image.


from Feedback OUT
from Signal OUT
to Signal IN
triggers here (special cable)
ANALOG OUT
High Speed
Precision
AXES
Out
Mod. In
VertIn
LaterIn
SumIn
PiezoShaker
Exc. In
Axis3 In
MONITOR
VertOut
LaterOut
SumOut
DIGITAL I/O
In
Out
POWER

CHAPTER

SIX

# THE MULTIFREQUENCY LOCKIN AMPLIFIER MLA™

The MLA™, also known as the Imtermodulation Lockin Analyzer ImMLA™, is a unique measurement instrument which could be described as a synchronous multifrequency waveform generator, digital oscilloscope, and real-time Fourier analyzing instrument. It is particularly powerful for *Intermodulation Measurement* but it can be used equally well for studying harmonics of a single drive, or any kind of multi-frequency response. The MLA™ can be configured in many different ways to perform many different measurements. Here we give a brief and general description of the MLA™ focusing on a technical description of the ports and how they may be configured.

The MLA™ is constructed from precision, low distortion, high speed analog-to-digital converters (ADC), digital-to-analog converters (DAC), and a highly parallel logic circuit called a Field Programmable Gate Array (FPGA). Different configurations of the MLA™ are realized by different firmware running on the FPGA. Contact **Intermodulaiton Products** if your experiment needs custom firmware. The different firmware configurations are accessed from the `Advanced` pull-down menu. Select `Load configuration` and choose the desired version. After making this selection, you must quit the software, cycle the power on the MLA™, and restart the software (in that order).

## 6.1 Capabilities

- **Triggering:** Up to 6 trigger ports are possible, any of which can either input or output a trigger signal, configurable to different voltage levels.
- **Inputs:** Total of 4 input ports. The sampling rate is configurable. Two high speed ADC are 14 bit, maximum 250 MSam/sec, and the other two ports are 16 bit, maximum 62.5 MSam/sec.
- **Outputs:** Two output ports have 16 bit DAC running at 500 MSam/sec. Up to 4 additional slow output ports are also possible with 16 bit DAC having a combined speed of 800 KSam/sec.
- **Lockins:** As many as 42 independent, non-interfering lockins can run simultaneously. At run-time the user can send a drive tone at each frequency, to either or both of the two output ports. The frequency, amplitude and phase of each drive tone is selected by the user at run-time. Both quadratures of response are measured at the user selected frequencies. Firmware controls the total number of frequencies, and the firmware controls which of 4 inputs will analyze the user selected frequencies. Analysis at more than 42 response frequencies is possible if you are willing to reduce the number of drive frequencies. Contact **Intermodulation Products** if your experiment needs custom firmware.

## 6.2 Connections

Your MLA may have a clean front panel with out any connections, as is the case when it is configured to be used with some AFM's where all connections are made from the back side via a composite cable. Consult the MLA configuration sheet delivered with your instrument to see the precise configuration of all connections for your instrument.

The standard connections are briefly described below:

**Front-side connections**

- TRIG 1 and TRIG 2 are trigger ports. In a standard configuration these are configured to receive End-of-Line (EOL) and End-of-Frame (EOF) trigger signals respectively.
- IN 1 and IN 2 are fast inputs which can operate at a maximum of 250 Msam/sec. The exact speed of these ports can be configured from the software. The frequencies analyzed at these inputs are set by your firmware configuration.
- IN 3 and IN 4 operate at a maximum of 62.5 Msam/sec. The exact speed of these ports can be configured from the software. The frequencies analyzed at these inputs are set by your firmware configuration.
- OUT 1 and OUT 2 are fast output ports. The user can specify at run-time which drive frequencies are sent to which output ports.
- OUT A , OUT B and OUT C are three slow output ports run-time controllable by the user, combined speed is 800 kSam/sec. A standard configuration uses OUT A for AFM feedback.

**Back-side connections**

- POWER is supplied to the MLA™ via an external power supply. Use only the power supply delivered from **Intermodulation Products**. Using any other supply voids the warranty.
- ETHERNET The MLA™ communicates with the computer via the Ethernet connection. The MLA™ may be directly connected to the Ethernet connection on the computer, or it may be be put behind an Ethernet router, switch or gateway.
- RF CLOCK IN and RF CLOCK OUT connections are used for synchronizing the internal clock of the MLA™ with the clock of some other piece of measurement equipment. They receive and send respectively, a 10MHz square waveform. Furthermore they are AC-coupled and have a voltage range of 2 Vpp. Other frequencies and voltage levels are available upon request. These ports are designed to connect to a 50 Ohm matching impedance and signal distortions may occur if the receiving or sending connection is not 50 Ohm on the other end.
- TRIG 3 and TRIG 4 are additional trigger ports. When running with an AFM using the composite connection to the AUX port, (e.g. Bruker Icon or FastScan), Trig 3 reads the EOL trigger and Trig 4 reads the EOF trigger.
- AUX is designed for a composite cable connection to certain AFMs (e.g. Bruker Icon and FastScan). This port may be empty with your version of the MLA™.

## 6.3 Firmware

There many possibilities to configure the lockin measurement by changing the firmware. The standard firmware uses a naming convention where the number of frequencies analyzed at each of the input ports is specified, as in the examples below for a 42 frequency lockin.

- IMP-42-0-0-0 : Response is analyzed at IN 1 only.
- IMP-0-0-42-0 : Response is analyzed at IN 3 only.
- IMP-21-21-0-0 : Response is analyzed at both IN 1 and IN 2, with 22 frequencies at each input.
- IMP-11-11-10-10 : Response is analyzed at all inputs IN 1 , IN 2, IN 3 and IN 4 with 11, 11, 10 and 10 frequencies respectively.

The 42 frequencies that are measured may also be chosen as drive frequencies. An output mask controls which drive frequency is applied to the ports OUT 1 or OUT 2 or both. If you do not want to drive and only analyze response at one frequency, simply set the drive amplitude to zero and set the mask so that frequency is not applied to either port.

Contact **Intermodulation Products** if these standard versions do not meet your needs <info@intermodulation-products.com>.

## 6.4 MLA version I (before 2015)

The original version of the MLA™ has one input port and two output ports. Contact Intermodulation Products, <info@intermodulation-products.com> if you would like to upgrade to the newer version.

### 6.4.1 Version I connections

**Front-side connections**

- `Signal OUT` sends the drive frequency comb to the shaker piezo of the AFM. The system is configured to work nicely with standard AFMs. Internal jumpers can be moved to change the output voltage range. Contact Intermodulation Products if you want different output range.
- `Feedback OUT` delivers a error signal to the host AFM, where zero volts corresponds to the set-point in the IMP Suite. When the host AFM is set to contact mode, with set-point zero in the host AFM software, The voltage sent by the Feedback Out port constitutes the error signal in the control of the AFM feedback. The feedback gains are set on the host AFM.
- `Signal IN` receives the detector signal from the AFM. The system is configured to work nicely with standard AFMs. Attenuators can be used to reduce the amplitude of the input signal if necessary. Contact Intermodulation Products if you want a different input range.
- `EOF TRIG IN` is the **End Of Line** signal which is generated by the host AFM and received by the MLA™.
- `EOL TRIG IN` is the **End of Frame** signal which is generated by the host AFM and received by the MLA™.

**Back-side connections**

- `+5V DC` powers the MLA™. One should always use the power supply delivered with MLA™. Using any other supply voids the warranty.
- `Ethernet` The MLA™ communicates with the computer via the Ethernet connection. The MLA™ may be directly connected to the Ethernet connection on the computer, or it may be be put behind an Ethernet router, switch or gateway.
- `10 MHz OUT` is a TTL sync signal for locking the MLA™ clock to external equipment.

### 6.4.2 Version I Firmware

Two basic versions are available

- IMP-2-23 : Two drive frequencies at the `Signal Out` port. 32 frequencies analyzed at the `Signal IN` port.
- IMP-24-24 : 24 drive frequencies at the `Signal Out` port and the same 24 frequencies are analyzed at the `Signal IN` port.

CHAPTER

SEVEN

# TROUBLE SHOOTING

Below is a list of problems that may arise, and solutions. Contact Intermodulation Products if you are having problems getting your system to operate <info@intermodulation-products.com>. There is a hidden program long file in each session folder **.internallog.dat** which the company representative may need to see if the problem can not be solved over the phone.

**Problem: The software crashed but the process is still running in the computer and I can not stop it.**
**Solution:** In Windows: tart the task manager (control+shift+escape). Look for **imp_suite.exe** and kill that process.

**Problem: I get only a very weak signal and I do not see any resonance when I do a frequency sweep.**
**Solution:** Did you make sure that the hardware switch on the signal access module in is the correct?

**Problem: I can not get a good fit to the noise calibration data.**

**Solution:**

- There may be a spurious signal coming from your AFM which happens to be close to resonance. Change cantilever and avoid the frequency of the spurious signal.
- You can exclude data points to avoid frequency bands where spurious signals and additional noise is getting in to you measurement.
- There may be an extra (not thermal) source of noise which is driving your cantilever. Make sure the drive from the host AFM is off and disconnected. Try turning off the high voltage drive to the Z-piezo in a tip-scanning AFM.

**Problem: When I open the software, only get the Analysis and Session Overview icons in the work flow.**
**Solution:** This means that the software can not find the MLA™ on the ether net. Check that the MLA™ is connected to the ether net, and verify that the computer has ether net connection to the MLA™.

CHAPTER

EIGHT

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